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Discomfort, performance degradation, and increased health risk have been associated with prolonged exposures to vibration occurring in the operation of civilian and military vehicles. While an increasing number of females are selecting these occupations, the existing vibration standards and exposure limits are based on the male population. The objective of this study was to compare the biodynamic responses of females and males exposed to whole-body vibration. This final report includes the evaluation of resonance behaviors observed in the driving-point impedance, and in the chest, head, and spine transmissibilities at two acceleration levels for the rigid seat and with the use of seat cushions. While the primary resonance frequency (4-8 Hz) was not significantly affected, the peak impedance magnitudes, normalized for body weight, were significantly less for the females as compared to the males. The chest transmissibility results were more variable. There was a tendency for the horizontal chest motion to be lower and the vertical chest motion to be higher in the females as compared to the males. No clear trends were observed in the vertical head and spine transmissibility peaks. The results indicated that differences exist between females and males in the distribution of mass, stiffness and damping properties of specific anatomical structures contributing to the observed biodynamic responses.

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INTRODUCTION

The operation of ground, air, and water vehicles can expose both civilian and military occupants to adverse and prolonged periods of whole-body vibration. These exposures have been associated with discomfort, performance degradation, and increased health risk (1, 2, 3, 4, 5, 6, 7). While occupations requiring the operation of heavy equipment and military air and ground vehicles have historically been dominated by males, an increasing number of females are choosing these occupations and are at risk of vibration exposure. Current vibration standards and recommended exposure limits, however, are primarily based on data collected from the male population (8,9). Differences between male and female anatomy and anthropometry are expected to affect their biodynamic response characteristics during vibration exposure raising questions about applying current vibration standards to females in order to minimize discomfort, performance degradation, and health effects. There have been no definitive studies which compare the effects of whole-body vibration between males and females and which assess the risk of the smaller female to the adverse effects of prolonged vibration exposure. A study recently conducted at Armstrong Laboratory used female and male military personnel to evaluate the effects of several military aircraft seat cushions on the transmission of vibration in the human body. The ultimate goal was to recommend cushion design criteria which would minimize vibration transmission and contribute to improved comfort. The three female individuals who volunteered for the study were among the 5th percentile of the general female population for weight, while the males were among the 50th and 95th percentile of the general male population for weight. Using driving-point impedance and transmissibility techniques, the results of the recent study showed that there were significant differences between the biodynamic responses of the small females and larger males. For vertical vibration exposure, the driving-point impedance magnitude associated with the primary resonance located between 4 and 8 Hz was lower for the smaller female, as expected, due to the lower mass. When normalized for body weight, the peak impedance responses were observed to be similar between subjects of the same sex, but significantly lower for the females as compared to the males (10). For exposures to vertical vibration, the smaller females showed significantly higher vertical chest transmissibility, but significantly lower horizontal chest transmissibility for the primary resonance response occurring between 4 and 8 Hz as compared to the males. The seat cushions were also found to affect the transmission of vibration in both females and males, increasing the magnitude of the primary resonance peak located between 4 and 8 Hz (11, 12). The objective of the current study was to expand the recent study to include a broader range of body weights in both female and male subjects in order to conduct a more critical evaluation and comparison between the vibration responses of females and males. This study includes the use of three seat configurations for comparing the effects of seat cushions on vibration transmission in the body. The driving-point impedance and transmissibility techniques were used to evaluate and compare resonance behaviors in the female and male subjects. A computerized visual acuity test was also included to evaluate the effects of vibration on visual performance. This final report covers the study period 1 Dec 94 to 30 Sep 95 and includes the analysis of resonance behavior observed in the driving-point impedance, and chest, head and spine transmissibilities at 0.59 and 2.35 m/s^2 rms (0.06 g_{rms} and 0.24 g_{rms}) acceleration levels.

METHODS

DATA COLLECTION AND REDUCTION

An electrodynamic vibration platform, manufactured by Unholtz-Dickie, was used to provide the vertical vibration exposures. A human test seat, designed to respond as a rigid mass over the frequency range of concern, was mounted on top of the platform and included a seatback, lapbelt, and double shoulder harness. For calculating the driving-point impedance, the transmitted force of the combined seat and human was measured by three load cells located between the seat and vibration platform. Two accelerometers were attached to the seat for measuring the input acceleration magnitude and phase. Vertical and horizontal transmissibilities resulting from vertical input vibrations at the seat were calculated from acceleration measurements using two miniature accelerometers placed on the chest (at the level of the manubrium), at the upper spine region (in the vicinity of the seventh cervical vertebra on the spinous process), and on a bitebar molded with dental acrylic. The input vibration at the seat included single sinusoidal frequencies as well as sum-of-sines profiles generated by combining discrete sinusoidal frequencies. The frequency components used for all input profiles ranged from 3 to 21 Hz in 1 Hz increments. The acceleration exposure levels were 0.59 and 2.35 m/s^2 rms (0.06 g_{rms} and 0.24 g_{rms}). Figure 1 illustrates the two sum-of-sines profiles. While the frequency content and rms acceleration were identical for the two profiles, the differences observed in their appearance was created by altering the phase relations between frequency components. The first sum-of-sines profile (Crest Factor = 2.9) is designated as P1, while the second profile (Crest Factor = 4.2) is designated as P2. A computer program was used to generate the vibration profiles and for simultaneously collecting all transducer data. Data were collected for two seconds at a sampling rate of 1024 Hz. A Fast Fourier Transform algorithm was used to calculate the transducer magnitude and phase difference between the sum of the three load cells and the input velocity calculated from the input acceleration at the seat. The impedance of the rigid seat (collected separately) was subtracted from the calculated impedance to obtain the impedance of the subject. Vertical and horizontal transmissibilities were calculated as the magnitude ratio and phase difference between accelerations measured at the chest, head, and spine (at the seventh cervical vertebra or C_7) and the vertical input acceleration at the rigid seat. Six tests were conducted on each subject. Each test consisted of exposing the subject to the two sum-of-sines profiles and to each sinusoidal frequency between 3 and 21 Hz at one of the two acceleration levels and for one of the three seat configurations. For each subject, three impedance and three transmissibility (at each site) frequency response profiles were obtained for each acceleration level and seat configuration. The frequency response profiles were used to evaluate and compare the frequency location and magnitude of the peak or resonance responses.

SEAT CONFIGURATIONS

Three seat configurations were used in the expanded effort including the rigid seat and two military aircraft seat cushions placed between the seat and subject. The first cushion (Cushion A) was obtained from a Black Hawk helicopter. The cushion is fabricated with three

layers of foam with different densities. The bottom layer is made of high density plastic foam and varies in thickness from about 1 cm at the back to 6 cm at the front, providing a contoured seat surface. Air vents run from the front to the back along the inside surface. The top layer consists of polyurethane foam about 2.5 cm thick. Sandwiched between these two materials is a layer of 1.5 cm thick polyurethane material similar to the top layer, but of greater density. The cushion is covered with black lambswool and weights 920.5 gm. The second cushion (Cushion B) was a prototype cushion designed for use in the ACES II ejection seat. The cushion is fabricated entirely of rate-sensitive foam and is approximately 3 cm thick. The cushion is encased in a cotton material with the top and side surfaces further covered with a thick treated wool fabric. The cushion is flat and weighs 1678.5 gm.

VISUAL ACUITY

Visual acuity was tested using a modified computer software program originally developed in the Visual Displays Branch of the Human Engineering Division, Crew Systems Directorate, Armstrong Laboratory. The program used the Snellen E test to evaluate visual performance. Subjects used a joystick to indicate the direction of the 'E' when flashed on the screen for a designated time period. Each size figure was flashed six to eight times in a random orientation (trial). If 75% of the responses were correct, the figure size would be decreased, otherwise, the size increased for the next trial. The last three trials were used to estimate the visual acuity and quantify the mean test score. The total time required to perform the visual acuity test was also recorded. A baseline visual acuity test was run twice prior to(B1) and following (B2) exposure to the vibrations. Two visual acuity tests were conducted for the following vibration exposures: both sum-of-sines exposures (P1 and P2), and at the sinusoidal frequencies of 5, 10, 16, and 20 Hz. The mean test score was calculated from the two acuity tests by averaging the number of correct answers for the last three trials. The mean test time was calculated by averaging the total test time for the two acuity tests.

SUBJECTS

The subject percentiles were according to body weight. The female subjects included three 5th percentile (5%) females, two 50th percentile (50%) females and one 95th percentile (95%) female. Originally, three 95% females were recruited, however, two of the subjects completed only the rigid seat tests. Unfortunately, additional 95% females could not be recruited for this study. The male subjects included three 5th percentile (5%) males, three 50th percentile (50%) males, and two 95th percentile (95%) males. During the tests, the subjects were loosely restrained by the lapbelt and shoulder harness for safety reasons. Subjects were instructed on the importance of maintaining an upright and consistent seated posture during testing. Subjects were asked to comment on any pronounced localized sensation of vibration or any sudden discomfort. The two most uncomfortable aspects of the exposures were documented. Female subjects were required to wear upper body athletic support clothing.

STATISTICAL ANALYSIS

The subjects were divided into six groups based on sex and weight percentile: 5% females, 50% females, 95% females, 5% males, 50% males, and 95% males. The values of the resonance frequency and the magnitude of the resonance peak (three of each obtained from the three frequency response profiles) were combined for subjects of the same sex and weight percentile. This provided up to nine frequency and magnitude data samples for each group depending on the number of subjects tested. One-Way Analysis of Variance (ANOVA) was performed on the data to determine if significant differences existed in the magnitude of the impedance and transmissibility resonance responses between the percentile groups. If significant differences were found, a *post hoc* pairwise multiple comparison test (Student-Newman-Keuls test) was used to compare these differences between the various groups. Statistical analysis was not performed on the resonance frequencies due to the variability within a subject under the testing conditions used in this study, and since the majority of percentile groups showed differences of 2 Hz or less. In addition, all resonance peaks were located within the critical frequency range of 4 and 8 Hz for the impedance, and the chest and head transmissibilities. However, differences in the resonance frequency means between percentile groups which were equal to or greater than 1.5 Hz were reported.

In order to evaluate the effects of the seat configurations and the acceleration level on the impedance and transmissibility resonance peaks, the One-Way Repeated Measures ANOVA was performed on the peak magnitude data collected for each group. In turn, the Student-Newman-Keuls pairwise multiple comparison test was used to identify significant differences between specific seat configurations and between the two acceleration levels. Again, statistical analysis was not performed on the resonance frequency data, but differences between the mean values which were equal to or greater than 1.5 Hz were reported.

For the visual acuity analysis, the One-Way ANOVA was used to evaluate differences in the mean test scores and mean test times between the females and males. The One-Way Repeated Measures ANOVA and Student-Newman-Keuls pairwise multiple comparison test was used to evaluate differences in the mean test scores and mean test times between the baseline (no vibration) conditions and for exposures to 5, 10, 16 and 20 Hz sinusoidal vibration; between the three seating configurations; and between the two acceleration levels.

RESULTS

The frequency location and magnitude of the primary resonance peaks were extracted from the frequency response profiles and evaluated for the driving-point impedance, both horizontal and vertical chest transmissibilities, vertical head transmissibility, and vertical spine (C_7) transmissibility. The normalized peak impedance was calculated by dividing the peak impedance magnitude response by the subject's body weight. Only the vertical transmissibility responses for the head and spine were compared between the percentile groups due to the minimal transmission

of vibration in the horizontal direction for these two sites. As mentioned previously, two of the three 95% females were eliminated from the study and did not participate in the cushion tests. In order to properly evaluate the effects of seat configuration and acceleration level, it was decided to use the three impedance and transmissibility profiles collected during each test from the remaining subject. For this reason, caution should be taken when evaluating and comparing the results for the 95% females.

IMPEDANCE RESPONSE

Body Weight Comparison

Figure 2 shows the means and standard deviations of body weights associated with each of the percentile groups tested in this study. As expected, there were significant differences in the body weights between percentile groups of the same sex. The figure shows that the weight variations within the groups were small, the largest weight range occurring in the 50% males. The figure also shows that the body weights associated with the 50% females and 5% males, and associated with the 95% females and the 50% males were similar. The similarity was significant only for the 50% females and 5% males. In general, the body weights of the male groups were higher as compared to the females. The exception occurred for the 95% females who weighed significantly more than the 5% males.

Group Effects on Resonance Behavior

Figure 3 shows the driving-point impedance magnitude frequency response profiles for the females and males exposed to discrete sinusoidal frequencies in the rigid seat configuration. The responses to both acceleration levels are included. In general, all frequency response profiles were similar with regards to the primary resonance behavior regardless of the type of exposure (sinusoidal vs sum-of-sines) and seat configuration. Differences in the peak responses due to the seat configurations are discussed below. As observed in previous studies (12, 13), additional regions of peak resonance responses can be observed in the impedance magnitude profiles. In this study, the first peak region was defined between 4 and 7 Hz. In most cases, this primary peak has been consistently observed and has the highest magnitude. The upper torso, including the shoulders and soft tissues and organs located within the chest cavity, has been considered the major contributor to this impedance peak (12, 13, 17). The second region was defined between about 7 and 9 Hz. At relatively low acceleration levels, the second peak as been observed to be of higher magnitude than the first peak. The peak observed in this region has been attributed to the dynamic response of the legs. In a previous study (12, 13), the second peak was observed for both 50% and 95% male subjects at an acceleration level of 0.49 m/s^2 rms, however, at a higher acceleration level of 2.45 m/s^2 rms, the peak appeared to become dampened. Preliminary modeling results predicted that the resonance frequency of the legs shifted downward at the higher acceleration levels, coinciding more closely with the location of the primary or first resonance peak. The thighs, in contact with the seat, have also been considered a contributor to the third peak region located between 10 and 14 Hz (14). The fourth peak region has been

associated with spine resonance where peak transmissibilities have been measured at the seventh cervical vertebrae (12,13). Magnitude peaks in the second, third, and fourth regions are not always observed in the impedance frequency response profiles and their appearance, as shown for the legs, can depend on the input acceleration level. Figure 3 shows that the females, particularly the 5% and 95% groups, produced higher responses at the second peak (7 - 9 Hz) when exposed to the lower acceleration level used in this study (0.59 m/s^2 rms). In some cases, the third peak region (10 - 14 Hz) appeared to have the highest magnitude. At the higher acceleration level (2.35 m/s^2 rms), the primary peak located between 4 and 7 Hz became more prevalent in the females, however, the second resonance peak was still observed for some subjects in the region of 7 to 8 Hz. It appears that the legs may have a significant influence on the impedance response of the females. Vibration data have been collected at the thigh and are currently being evaluated. In contrast, the males, particularly the larger 50% and 95% groups, showed very distinct peaks in the first region of resonance located between 4 and 7 Hz, although additional peak regions were observed at higher frequencies. The additional peaks located beyond the primary peak appeared to be more dampened at the higher acceleration level in the male subjects. The larger males also showed higher peaks as compared to the smaller females. Since the resonance behavior observed at the first peak located between 4 and 7 Hz has generally been considered the region of greatest human sensitivity, this was the region used for comparing the resonance frequencies and peak responses between the percentile groups.

Primary Impedance Resonance Frequency. Figure 4 shows the means and standard deviations for the primary impedance resonance frequency observed between 4 and 7 Hz for each group at the two acceleration levels and for the three seat configurations. The majority of data showed differences in the peak frequency of 2 Hz or less between percentile groups. Differences of 1.5 Hz or greater in the mean peak frequencies between percentile groups are discussed below. For the rigid seat, the 95% female showed the same peak frequency for all three exposures at both acceleration levels. When comparing the mean frequencies, the 50% females showed a higher frequency (greater than 1.5 Hz) than the 95% female at the higher acceleration level, otherwise, all peak frequencies were within 1.5 Hz of each other among the six groups. With the use of Cushion A, all peak frequencies were quite similar among the six percentile groups, showing differences of less than 1.5 Hz in the mean values. Cushion B did show differences of 1.5 Hz or greater in the mean peak frequency between certain groups. At the lower acceleration level, the 5% females and all male groups showed a higher mean frequency as compared to the 95% female. The 95% female showed all peak responses occurring at 4 Hz which was the lowest resonance frequency observed in this study.

Primary Peak Impedance Magnitude. Figure 5 shows the means and standard deviations for the primary peak impedance magnitudes at both acceleration levels for the three seat configurations. The figure shows that, particularly among the males, the peak impedance magnitude increased with body weight. The male responses also appeared to be higher as compared to the females. Figure 6 summarizes the statistical results for the mean peak impedance magnitude at each acceleration level. The three shades represent the three seat configurations. The percentile groups listed in the first column are compared to the percentile groups listed along the diagonal.

Lines directed upwards and to the right indicate that the peak impedance magnitudes associated with the percentile group listed in the column were found to be significantly greater than the peak impedance magnitudes of the percentile group listed diagonally. Likewise, lines directed downward and to the right indicate that the column group peaks were significantly less than the diagonal group peaks. The absence of lines indicates that there was no significant difference between the groups. At both acceleration levels, all percentile groups showed significantly higher impedance peaks as compared to the 5% females for all seat configurations. The larger 95% males showed significantly higher peaks as compared to the 50% males who, in turn, showed higher peaks than the 5% males for all seat configurations at both acceleration levels. Both the 50% and 95% males showed significantly higher peaks as compared to the remaining groups for all configurations. No significant differences were observed between the 50% and 95% females and between the 95% females and 5% males for all seat configurations at both acceleration levels. The 50% females were similar to the 5% males with the use of Cushion B at the lower acceleration level, but showed no significant differences at the higher acceleration level for any of the seat configurations.

Normalized Peak Impedance. In order to determine if body weight was responsible for the differences observed in impedance magnitude, the impedance was normalized by dividing the peak response located between 4 and 7 Hz by the subject body weight. Figure 5 includes the means and standard deviations for the normalized peak impedance ratios. The figure indicates that the normalized peak impedance tended to be higher in the males as compared to the females with similar peaks observed between groups of the same sex. Figure 7 summarizes the statistical results for each of the seat configurations at the two acceleration levels. In contrast to the peak impedance magnitude results shown in Figure 6, there were no significant differences in the normalized peak impedance among the females at both acceleration levels except with the use of Cushion B. For this seat configuration, the 95% females showed a significantly lower ratio as compared to the 5% and 50% females. Among the males, significant differences were also observed with the use of Cushion B; the 95% males showed higher ratios as compared to the 5% males, and lower ratios as compared to the 50% males at the lower acceleration level. Both the 50% and 95% males showed higher ratios as compared to the 5% males for the rigid seat and Cushion B at the higher acceleration level. All male groups showed significantly higher normalized impedance ratios as compared to the females for all three seat configurations at the lower acceleration level. At the higher acceleration level, the results were variable, however, any significant differences were observed as higher ratios in the males as compared to the females. The 5% males showed the greatest similarity with the female results at the higher acceleration level. All male groups showed significantly higher ratios as compared to the females with the use of Cushion B. The normalized impedance results strongly suggest that differences in the vibration response among groups of the same sex may be primarily due to differences in body weight, however, differences between females and males may depend on other factors.

Acceleration Effects

Although differences in the location of the resonance frequencies did not vary by more than 2 Hz in most cases, Figure 4 shows that there was a tendency for the mean primary resonance frequency to shift downward at the higher acceleration level. Differences in the mean resonance frequencies between the two acceleration levels were within 1.5 Hz among each of the groups for all seat configurations. The downward shift in the location of the resonance frequency with increasing acceleration has been observed previously (13), but the shift was usually less than 2 Hz. All female groups showed similar impedance magnitude resonance peaks at both acceleration levels with the use of the rigid seat. The 5% females showed that the resonance peaks associated with the lower acceleration level were significantly higher than the resonance peaks observed at the higher acceleration level for Cushion A, while the 50% females showed that the resonance responses for Cushion B was significantly higher at the lower acceleration level. The effects of acceleration level were more apparent for the male groups. All male groups showed significantly higher impedance magnitude resonance peaks at the lower acceleration level for all seat configurations except for the 95% males and the rigid seat. In this case, the resonance peaks were similar at both acceleration levels.

Seat Configuration Effects

For the primary impedance resonance frequency, only the 50% females in the rigid seat configuration showed mean peak frequencies which were 1.5 Hz or higher than frequencies observed with the use of the two cushions, however, all differences were less than 2 Hz. Figure 8 shows the impedance resonance magnitude means and standard deviations for the three seat configurations. The statistical analysis indicated that there were significant effects of the seat configuration on the magnitude of the primary impedance resonance peak depending on the percentile group and the acceleration level, although these differences were not dramatic. All females showed a tendency for the highest primary resonance peak to occur with the use of Cushion A, particularly as compared to the rigid seat configuration. Only the 5% and 50% females showed that, at both acceleration levels, the resonance responses were significantly higher with the use of Cushion A as compared to both the rigid seat and Cushion B. The results for Cushion B were variable; the resonance responses were either equal to or greater than the rigid seat responses, or equal to or less than the peak responses associated with Cushion A. The 95% females showed no significant effect of seat configuration. All male groups showed a higher primary impedance resonance peak with the use of Cushion A as compared to the rigid seat at the lower acceleration level, but no significant differences between these two seat configurations at the higher acceleration level. At the lower acceleration level, as with the females, the impedance resonance response associated with the use of Cushion B was either equal to or greater than the resonance response observed using the rigid seat, or either equal to or less than the resonance response observed with the use of Cushion A. At the higher acceleration level, the only significant differences between seat configurations observed for the males occurred for the 95% group. Both the rigid seat and Cushion A produced higher resonance magnitude peaks than Cushion B.

CHEST TRANSMISSIBILITY

Group Effects on Resonance Behavior

Figures 9 and 10 show the horizontal (X) and vertical (Z) chest transmissibility frequency responses, respectively, for the sinusoidal exposures using the rigid seat configuration. In general, all profiles showed similar responses with regards to the primary resonance behavior regardless of the type of exposure (sinusoidal vs sum-of-sines) and seat configuration. Differences in the resonance responses due to the seat configurations are discussed below. Figure 9 shows that there can be significant horizontal (fore-and-aft or X) motion in the upper torso resulting from vertical vibration exposure. While the majority of females showed peak transmissibility responses which were around 1.0 or less, the male subjects showed higher responses, particularly at the lower frequencies. Both the females and males showed a peak response between 4 and 7 Hz, but also showed additional peaks at higher frequencies. For the males, the additional resonance peaks, located beyond the primary resonance (4 - 7 Hz), tended to be of lower magnitude as compared to the primary peak. For the females, the additional resonance peaks tended to be of similar or even higher magnitude as compared to the primary peak. Figure 10 shows that both males and females produced dramatic transmissibility resonance peaks for the vertical (Z) chest motion in the vicinity of 4 to 7 Hz with the females showing somewhat higher magnitudes. Again, additional resonance peaks were observed at higher frequencies. The significant transmissibility resonance peaks observed between 4 and 7 Hz in both the horizontal and vertical chest transmissibilities were associated with the region of greatest human vibration sensitivity and reflected the contribution of the upper torso to the first region of resonance or the primary resonance peak observed in the impedance data. The presence of horizontal chest motions during vertical exposures is most likely due to forward bending or rotation of the upper torso. The additional resonance magnitude peaks coincided with the regions of resonance observed in the impedance data located beyond the primary region of 4 to 8 Hz, and may be the result of coupled motions between anatomical structures. Comparisons were made between the frequencies and the transmissibility magnitude ratios associated with the first or primary peak located between 4 and 7 Hz.

Primary Horizontal (X) and Vertical (Z) Chest Resonance Frequencies. Figure 11 shows the means and standard deviations for the resonance frequencies associated with the horizontal and vertical chest transmissibilities at both acceleration levels for all three seat configurations. Again, the majority of data showed that the peak frequencies among the percentile groups were within 2 Hz of each other. For the mean peak frequencies associated with horizontal motion using the rigid seat, the only differences which were 1.5 Hz or greater occurred between the 5% males and 95% females, and the 50% males and 50% females at the lower acceleration level. All differences in the mean peak frequency were less than 1.5 Hz for the horizontal chest transmissibilities with the use of Cushion A. With the use of Cushion B, the 5% females and 50% males showed a higher mean peak frequency for the horizontal chest transmissibility as compared to the 95% female at the lower acceleration level. For all three seat configurations and both acceleration levels, the mean resonance frequencies observed for the vertical chest transmissibilities were

within 1.5 Hz among the six groups.

Primary Peak Horizontal (X) and Vertical (Z) Chest Transmissibilities. Figure 12 shows the means and standard deviations for the peak horizontal and vertical chest transmissibilities at both acceleration levels and for the three seat configurations. The figure shows a tendency for the peak horizontal chest transmissibilities to be higher in the males as compared to the females, while the peak vertical chest transmissibilities appeared to be higher in the females as compared to the males as suggested by the frequency response profiles. Figures 13 and 14 summarize the statistical results for the peak horizontal chest transmissibilities and peak vertical chest transmissibilities, respectively. The statistical results for the chest transmissibilities are more variable as compared to the results for the peak driving-point impedance and normalized impedance. In general, the 50% females showed significantly higher peaks as compared to the 5% and 95% females at the lower acceleration level while less differences were observed among the females at the higher acceleration level. At both acceleration levels, there were minimal differences among the males relative to the seat configuration. At the lower acceleration level, the majority of results showed that all males produced significantly higher peak horizontal chest transmissibilities as compared to the 5% and 95% females, however, minimal differences were observed between the males and the 50% females for all seat configurations. At the higher acceleration level, all males did show a significantly greater peak transmissibility as compared to the 95% females with the use of Cushion B while the 5% males showed higher peaks than the 5% and 95% females with the use of Cushion A. No other significant differences were observed between the females and males at the higher acceleration level. While higher horizontal chest transmissibilities suggest that the males may produce larger forward flexion in the upper torso during whole-body vibration, the motion appears to depend on the acceleration level.

For the peak vertical transmissibilities, there were variable differences among the females at the lower acceleration level with no significant differences observed between the 5% and 95% females. No significant differences were observed among the females at the higher acceleration level for any of the seat configurations. There was a significantly higher vertical peak observed for the 95% males as compared to the 50% males for all seat configurations at the lower acceleration level. At both acceleration levels, there were no significant differences in the peak vertical chest transmissibility between the 95% males and 5% and 95% females for all three seat configurations. No significant differences were observed between the 5% males and 95% females at the higher acceleration level for all seat configurations. As illustrated in Figure 14, significant differences occurring between the females and 5% and 50% males showed higher peaks for the females.

Acceleration Effects

Although Figure 11 indicates that there was a tendency for the primary resonance frequencies to shift downward at the higher acceleration level for both the peak horizontal and peak vertical chest transmissibilities, differences between the mean frequencies at the two acceleration levels were less than 1.5 Hz. Figure 12 shows variable effects of acceleration level

on the peak transmissibility magnitudes. All female groups showed no effects of the acceleration level on peak horizontal chest transmissibility with the use of Cushion B. The 5% females showed significant differences with the rigid seat, while the 50% females showed significantly differences with the use of Cushion A. In both cases, the peak responses were higher at the lower acceleration level. All three male groups showed no effects of the acceleration level on the peak horizontal chest transmissibility with the use of Cushion A. The 5% and 95% males showed significant differences with the use of Cushion C, while the 50% and 95% males showed significant differences with the rigid seat configuration. As with the females, the peak responses were higher at the lower acceleration level. The results suggest that any effect of the acceleration level on horizontal chest transmissibility is similar to the observations for impedance: increasing the acceleration level tends to decrease the magnitude of the peak response.

The 5% and 95% females showed no effects of acceleration on the peak vertical chest transmissibility for all seat configurations. The 50% females showed significantly higher peaks at the higher acceleration level for both cushions. No significant acceleration effects were observed for the male groups with the use of cushions. The 50% and 95% males did show higher peaks at the higher acceleration level with the use of the rigid seat. The acceleration level appears to have the opposite effect on the vertical chest transmissibility as compared to the horizontal chest transmissibility: increases in the acceleration level appears to result in increases in the peak magnitude response.

Seat Configuration Effects

Figure 15 shows the means and standard deviations for the peak horizontal chest transmissibilities associated with each of the seat configurations for comparison. The 95% females and 95% males showed no effect of the seat configuration on the peak response. At the lower acceleration level, all remaining groups showed significantly higher peaks with the use of Cushion A as compared to the rigid seat. This was also true at the higher acceleration level except for the 5% females who showed similar responses. The significance of differences between Cushion B and the other seat configurations were variable among the subjects, however, the peak responses for Cushion B were either equal to less than the responses for Cushion A, and either equal to or greater than the responses for the rigid seat.

Figure 16 shows the means and standard deviations for the peak vertical transmissibilities associated with each seat configuration for comparison. For the vertical transmissibilities, the majority of subjects showed that the peak responses using Cushion A were the highest among the three seat configurations, particularly when compared to the rigid seat. The 50% females showed no significant effects of seat configuration at the lower acceleration level, while the 95% females showed no significant effects at the higher acceleration level. In addition, the peak responses associated with the use of Cushion A were significantly higher than the responses observed with the use of Cushion B for the males. For the females, the effects of Cushion B were variable; the peak response being either equal to or less than the response for Cushion A, or either equal to or greater than the response observed for the rigid seat. Figure 16 does show that the greatest effect

of cushions on vertical chest transmissibility appeared to occur for the females.

HEAD TRANSMISSIBILITY

Group Effects on Resonance Behavior

Figure 17 shows the vertical (Z) head transmissibility frequency response profiles for the females and males for the sinusoidal exposures at both acceleration levels. In general, these profiles are representative of the head transmissibility data collected in this study. Specific differences in the peak responses are discussed in subsequent sections. The figure shows that a pronounced peak in the vertical head transmissibility occurred primarily between 4 and 7 Hz, coinciding with both the primary peak impedance magnitude and peak chest transmissibilities. A second peak was observed between about 10 and 16 Hz. The data suggest that the first peak occurred due to coupling between the head and upper torso, while the second peak may be due to coupling between the head and spine since the spine shows a peak response at the higher frequencies (See Spine Transmissibility). It does appear that the males showed a higher peak between 4 and 7 Hz as compared to the females. For both the females and males. The peak responses appeared to be of reduced magnitude at the higher acceleration level.

Primary Vertical (Z) Head Resonance Frequency. Figure 18 shows the means and standard deviations for the primary head resonance frequency located between 4 and 7 Hz at both acceleration levels and for the three seat configurations. For the rigid seat, the only differences in the mean peak frequencies which were equal to or greater than 1.5 Hz occurred between females and males. Both the 5% and 50% males showed higher peak frequencies as compared to the 50% and 95% females at the lower acceleration level. With the use of Cushion A, the location of the mean peak frequencies were all within 1.5 Hz between all groups. With the use of Cushion B, the 95% females showed a mean peak frequency which was at least 1.5 Hz higher as compared to the 50% females at the lower acceleration level. The 95% females also showed a higher peak ($\geq$ 1.5 Hz) as compared to the 5% males at the lower acceleration level and the 95% males at both levels for Cushion B. The 50% males showed a 1.5 Hz or greater difference in the location of the mean peak frequency as compared to the 50% females at the lower acceleration level using Cushion B.

Primary Peak Vertical (Z) Head Transmissibility. Figure 19 illustrates the means and standard deviations for the peak vertical head transmissibilities located between 4 and 7 Hz at the two acceleration levels for the three seat configurations. Figure 20 summarizes the statistical results which compare the percentile groups for each seat configuration at the two acceleration levels. The figure shows that there were no significant differences in the peak head transmissibility between the females for any of the seat configurations at the two acceleration. Among the males, significant differences were only observed at the lower acceleration level. The 95% males produced a higher peak than the 5% males for the rigid seat, while a significantly higher peak was observed in the 5% males as compared to the 50% and 95% males with the use of Cushion A. Minimal differences in the peak response were also observed between the females and males. At the lower acceleration level, the 95% males showed significantly higher peaks as compared to the

5% and 50% females for the rigid seat, while both the 50% and 95% males showed lower peaks than the 50% females with the use of Cushion A. At the higher acceleration level, the only significant effect was a lower head transmissibility peak observed in the 50% males as compared to the 5% females with the use of Cushion B.

Acceleration Effects

Figure 18 shows that the head resonance frequency tended to shift downward in value with an increase in acceleration level, similar to the results observed for impedance and the horizontal chest resonance frequencies. The only differences which were equal to or greater than 1.5 Hz occurred for the 5% and 50% males for the rigid seat; and the 95% females, 50% males, and 95% males with the use of Cushion B. There were variable effects of acceleration level on the peak vertical head transmissibility. Figure 19 does show a tendency for the response to be lower at the higher acceleration level. For the rigid seat configuration, all males showed that these differences were significant, while only the 95% females showed significant effects of acceleration. With the use of Cushion A, the 95% females and 5% males showed significant acceleration effects. For Cushion B, the 5% females, and 50% and 95% males showed significant acceleration effects.

Seat Configuration Effects

The only differences in the mean resonance frequencies which were equal to or greater than 1.5 Hz between the seat configurations occurred at the lower acceleration level. The 95% females showed a higher peak frequency with the use of Cushion B as compared to the rigid seat, while the 5% males showed that the rigid seat resulted in a higher peak frequency as compared to Cushion A. Figure 21 shows the means and standard deviations for the peak vertical head transmissibility associated with each of the seat configurations for comparison. As compared to the chest results, the peak head transmissibilities did not show any clear trend in seat configuration effects. The 5% females did show a significantly higher peak at the lower acceleration level with the use of Cushion B as compared to the rigid seat and Cushion A. All females showed no significant effects of the seat configuration on the peak response at the higher acceleration level. The 50% and 95% males showed similar responses for all three seat configurations at the higher acceleration level, while the 95% males showed a significantly higher peak with the use of the rigid seat and Cushion B as compared to Cushion A at the lower acceleration level. The 5% males showed that Cushion A resulted in a higher peak as compared to the rigid seat and Cushion B at both acceleration levels.

SPINE TRANSMISSIBILITY

Group Effects on Resonance Behavior

Figure 22 shows the vertical (Z) spine transmissibility frequency responses for the sinusoidal exposures at the two acceleration levels using the rigid seat configuration. In general, these profiles are representative of the data collected in this study. The figures shows that, in the

majority of the data, the highest spine transmissibility occurred in the frequency range of 12 to 18 Hz. Smaller peaks were observed in the range of 4 to 7 Hz which coincided with the primary impedance resonance peak, and the chest and head transmissibility peaks. This peak has been associated with coupling of motion between the spine and upper torso (13). In some cases, additional peaks were observed between about 10 and 12 Hz. It is speculated that these peaks may be due to coupling with other resonance structures, or that the spinal column may have additional resonances. The frequency location and the magnitude of the peak transmissibility responses located primarily between 12 and 18 Hz were used for comparing the percentile groups and for evaluating the effects of seat configuration and acceleration level.

<u>Primary Vertical (Z) Spine Resonance Frequency.</u> Figure 23 shows the means and standard deviations for the spine resonance frequencies located between 12 and 18 Hz. Differences between the resonance frequencies among groups of the same sex and between the females and males were quite variable and greater than 1.5 Hz as compared to the resonance frequencies associated with motions at the lower frequencies (impedance, chest, and head). The most prominent observation was the relatively lower peak frequencies occurring for the 95% males as compared to the other percentile groups, particularly the 5% and 50% females and males. For these males, the peak spine response occurred at relatively lower frequencies ranging between 9 and 14 Hz. As mentioned previously, these lower resonance frequencies may be associated with coupling or to additional spine resonances. This suggests that the peak spine transmissibility at the higher frequencies was dampened in these larger males and was not easily observed in the frequency response profiles.

<u>Primary Peak Vertical (Z) Spine Transmissibility.</u> Figure 24 shows the means and standard deviations for the primary peak spine transmissibilities. The figure shows that there were large variations in the transmissibilities among the groups rendering it difficult to observed specific trends. Figure 25 summarizes the statistical results and confirms that there were no significant differences between any of the percentile groups.

<u>Acceleration Effects</u>

Figure 23 shows a tendency for a downward shift in the frequency location of the peak spine transmissibility with increased acceleration for some subjects. These shifts were equal to or greater than 1.5 Hz for the 50% females using Cushion B, for the 95% females and all seat configurations, and for the 50% males using the rigid seat and Cushion A. In addition, the differences in the resonance frequencies observed for the 50% females with the use of Cushion B, and the differences observed for the 95% females with the use of the rigid seat and Cushion B were equal to or greater than 2 Hz. For the magnitude of the peak spine transmissibility, no clear trends were observed. However, the 5% females showed significantly higher peaks at the lower acceleration level using the rigid seat, while the 50% males showed significantly higher peaks at the lower acceleration level with the use of Cushion B.

Seat Configuration Effects

For the 50% females, Cushion B showed a higher resonance frequency at the lower acceleration level, and a lower resonance frequency at the higher acceleration as compared to the other seat configurations. These differences were equal to or greater than 1.5 Hz but less than 2 Hz at the lower acceleration level, and greater than 2 Hz at the higher acceleration level. The 95% females showed that both the rigid seat and Cushion B resulted in a higher resonance frequency than Cushion A at the lower acceleration level. The difference was 2 Hz between the cushions. The 5% males showed a lower resonance frequency using Cushion A as compared to Cushion B ($\geq$ 1.5 Hz). Figure 26 shows the peak spine transmissibilities relative to the seat configuration. While large variations were observed in the data, there was a tendency for the peak associated with the rigid seat to be greater than the peak occurring with the use of cushions. These differences were only significant for the 5% females between the rigid seat and both cushions, and for the 50% males between the rigid seat and Cushion A. Cushion B showed peaks which were similar to the rigid seat for the 50% males. The tendency for lower spine transmissibility peaks with the use of seat cushions is opposite to the trends observed in the peak impedance and peak chest transmissibilities where the cushions tended to amplify the transmission of vibration. It appears that, at relatively higher frequencies, the cushions either have no effect, or tend to dampen the transmission of vibration to the upper spine depending on the cushion material. This does raise questions about the effects of seat cushions on the head transmissibility at higher frequencies where peaks were observed in the frequency response profiles. These effects are being evaluated.

VISUAL ACUITY

Figure 27 shows the mean test scores and mean test times ± one standard deviation calculated for each acceleration level and each seat configuration for the female and male percentile groups.

Female/Male and Seat Configuration Effects

There were no significant differences in the mean test scores and mean test times between the females and males and between the three seat configurations.

Vibration Exposure Frequency and Acceleration Effects

As mentioned in **METHODS**, the One-Way Repeated Measures ANOVA was use to evaluate the significance of exposure frequency and acceleration level on visual performance. Significant differences between responses may not be easily observed in Figure 27 since the means include data for all subjects. At the lower acceleration level, the only significant difference occurred in the mean test scores for exposures using Cushion A. The scores for the 5 Hz exposures were less than the baseline tests and less than the scores for the 20 Hz exposures and the two sum-of-sines exposures (P1 and P2 in Figure 27). For the rigid seat configuration at the

higher acceleration level, the mean test scores collected during the vibration exposures (P1, P2, 5, 10, 16, and 20 Hz) were similar, but only the scores associated with 5, 16, and 20 Hz were significantly lower than the baseline scores. For the rigid seat, the test times at 5 and 16 Hz were significantly longer as compared to the final baseline score (B2). With the use of both cushions, all baseline test scores were significantly greater than the scores collected during exposures to the sinusoidal frequencies (5, 10, 16, and 20 Hz) with variable results for the sum-of-sines exposures (P1 and P2). For Cushion A, the test score results between all vibration exposures were similar. The test times were significantly longer for the sinusoidal exposures as compared to the final baseline (B2) but not necessarily longer as compared to the initial baseline (B1). The test times were similar among all vibration exposures with the use of Cushion A. For Cushion B, the test scores associated with the sum-of-sines exposures were greater than the scores for the 10 Hz exposures while no other significant differences were observed between the scores for the vibration exposures. For Cushion B, the test times collected during all vibration exposures were significantly longer than the initial baseline (B1). The test times for the 5 and 10 Hz exposures were significantly longer than the first sum-of-sines signal (P1) and for the final baseline (B2).

Figure 27 shows a tendency for reduced mean test scores increased mean test times at the higher acceleration level. An asterisk is used to mark those exposures and seating conditions which showed significant differences in the measurements relative to the vibration level. The most dramatic effect of acceleration level occurred with the use of Cushion A; all vibration exposures showed a decrease in the score with the increase in acceleration level. In addition, the test times for both sum-of-sines exposures and for the 5 Hz and 20 Hz exposures were significantly longer at the higher acceleration level with the use of Cushion A. The second sum-of-sines exposure (P2) showed a significantly longer test time at the higher acceleration level with the use of Cushion B. The results strongly suggested that visual acuity is reduced during sinusoidal vibration, regardless of the frequency, as compared to the no vibration condition. However, the results were inconclusive for the combined frequencies or sum-of-sines exposures. In addition, increasing the acceleration level tends to reduce visual acuity, however, the significance of these results depends on the seat configuration.

SUBJECTIVE RESPONSES

At the low acceleration level, there were minimal complaints about discomfort, although all subjects commented that the vibration between 4 and 8 Hz (particularly at 5 Hz) produced the largest body motions. Many subjects reported that the motions were felt in the whole body. For the exposures to sinusoidal frequencies of 4 to 5 Hz, the females reported excessive motions in the breast region which were quite uncomfortable. The discomfort occurred for all seat configurations and was particularly pronounced at the higher acceleration level. All subjects reported blurring of their vision at higher frequencies above 10 Hz at the higher acceleration level. Comments were specifically directed at difficulty in seeing the smaller Snellen 'E'. The visual acuity results, however, indicated that the reduction in visual performance was independent of the exposure frequency.

DISCUSSION

The results of this study show that differences do exist between females and males in their biodynamic responses during exposure to whole-body vibration. The magnitude of the primary driving-point impedance peak was expected to be a function of body weight, i. e., higher magnitude with higher weight, as observed in the data. When the impedance peak data was normalized by dividing by the subject body weight, the results strongly suggested that total body weight was the key factor in differences observed between subjects of the same sex, but that the distribution of mass, stiffness, and damping properties among those anatomical structures contributing to the primary impedance resonance were different between females and males. These conclusions were also based on the observation that there were no clear differences in the resonance frequencies associated with the primary peak impedance response among both females and males. In addition, the higher incidence of resonance behavior observed for the females in the impedance frequency response profiles between 7 and 9 Hz further supports differences between females and males in the mass, stiffness, and damping of specific anatomical structures sensitive to vibration exposure. The impedance peaks observed between 7 and 9 Hz have been associated with leg resonance.

Since the driving-point impedance technique only provides information on the location and magnitude of resonance behavior, and not on those anatomical structures which are the primary contributors to the observed behavior, it was speculated that the transmissibility technique, when used to evaluate the motions of specific anatomical regions, would further delineate the key factors affecting the differences in the biodynamic responses of females and males. For the chest transmissibilities, as with the impedance results, no clear differences were observed in the primary resonance frequency located in the sensitive region of 4 to 8 Hz between females and males. However, even though significant differences were observed in the chest transmissibilities among subjects of the same sex, there was a strong tendency for the peak horizontal chest transmissibility magnitude to be greater in the males, while the peak vertical chest transmissibility magnitude was greater in the females. The observations in the horizontal chest transmissibility implied that there may be greater forward flexion in the upper torso of the males. Although not contributing directly to the observed differences in the impedance response, these findings do raise questions about the significance of factors such as sitting height, particularly for differences which may occur during multi-axis vibration exposures. Since the upper torso is considered a major contributor to the primary resonance peak observed in the impedance data (12, 13, 17), these findings specifically imply that the mass, stiffness, and damping properties of the upper torso are different between females and males. In addition, the uncomfortable motions reported in the soft tissues of the chest by the females further supports the significance of these results and their implications. Interestingly, the peak transmissibility responses measured at other anatomical sites, including the head and spine (C_7), were similar among all percentile groups.

As mentioned, the results of this study showed no clear differences in the location of the primary impedance and chest transmissibility resonance frequencies for the test conditions and evaluation procedures used in this study. It was observed that the majority of the primary peaks

primary impedance and chest transmissibility resonance frequencies for the test conditions and evaluation procedures used in this study. It was observed that the majority of the primary peaks for the impedance and chest transmissibilities were within 2 Hz of each other among the subjects. In addition, all resonance frequencies occurred between 4 and 8 Hz, or within the frequency region of greatest human vibration sensitivity for vertical exposures. Regardless of the differences in the magnitudes of the resonance responses, the results of this study do imply that current vibration exposure standards reflect the frequency sensitivities of both females and males.

It is known that higher acceleration levels tend to shift the location of the primary resonance frequency downward by 1 to 2 Hz (13, 14). The results of this study also showed the tendency for a downward shift in the resonance frequency at the higher acceleration level. In addition, there was also a tendency for a lower magnitude peak at the higher acceleration level except for the vertical chest transmissibility which showed a tendency for a higher peak at the higher acceleration level. Not all of the magnitude shifts were statistically significant. In general, it did appear that less differences were observed in the transmissibilities between percentile groups at the higher acceleration level. Both in this study and in a previous study (13), higher acceleration levels tended to dampen the appearance of additional impedance resonance behavior located beyond the primary peak. In this study, this effect was particularly marked for the male subjects when comparing the impedance resonance behavior at the two acceleration levels.

In general, seat cushions tend to increase the transmission of vibration at low frequencies but dampen the vibration at higher frequencies, depending on the cushion material properties (11,15). It appears that conventional foam cushions, as well as the helicopter and rate-sensitive seat cushions tested in this laboratory, have little if any effect on the frequency location of the impedance or chest transmissibility peak responses observed between 4 and 8 Hz. The results of this study are in agreement with a previous study (11) which showed a tendency for increases in the magnitude of the primary peak responses observed for impedance and for the chest transmissibilities at the lower frequencies. These increases appeared particularly marked in the vertical chest transmissibility peaks observed for the females, where higher upper torso motions were already observed for the rigid seat configuration. In addition, Cushion A also tended to dampen the transmissibility peak observed for the spine at the higher frequencies. The effects of a seat cushion depends on its material properties, i.e., the mass, stiffness, and damping characteristics. Using rigid mass tests, Cushion A showed lower stiffness and damping coefficients as compared to Cushion B, although their damping factors were quite similar (11). Regardless of their material properties, current cushion designs, similar to those tested in this laboratory, would be ineffective mechanisms for minimizing the transmission of vibration to the upper torso in the critical frequency range of 4 to 8 Hz.

The visual acuity test was established as the consequence of previous vibration studies in which subjects reported significant visual blurring at the higher frequencies. The visual acuity test did show that, regardless of the percentile group, vibration exposure caused visual performance degradation as compared to the no vibration condition. However, the test did not delineate differences due to frequency. Cushion A was associated with the most significant degradation of

visual acuity with increasing acceleration level for all vibration exposures, regardless of its dampening effect in the spine at higher frequencies. As mentioned previously, resonance behavior observed at higher frequencies in the head transmissibility data has not been evaluated but may provide valuable information concerning the association of vibration and the reports of visual degradation. Modifications to the visual acuity test are being considered which may increase test sensitivity.

A five degree-of-freedom lumped-parameter model, which includes representation for the major dynamic anatomical structures or regions, has been used to simulate human vibration response (13). The model has been modified to include cushion stiffness and damping properties and was shown to be relatively effective in predicting the observed trends in the driving-point impedance and vertical chest transmissibility with the use of Cushions A and B (11). The data collected in this study provides valuable biodynamic information for simulating the differences in the impedance and chest transmissibility between the females and males. The model could be used to define the specific differences in the mass, stiffness, and damping properties of the upper torso which are responsible for the observed responses. The evaluation of other biodynamic response data, including the leg transmissibility and the additional resonance behaviors observed in the head transmissibility, will be necessary before any improvements are recommended to the current vibration exposure standards. It is not the intent of the author to use the data collected in this study or any follow-on studies to establish separate vibration exposure criteria for females and males. The goal is to develop guidelines for improving equipment and operational procedures and to recommend exposure criteria which will improve the comfort, performance, and health of all individuals who choose occupations which expose them to whole-body vibration.

CONCLUSIONS

The following conclusions are based on the trends and statistical findings observed for the test conditions and evaluation methods used in this study:

1. In general, no clear differences were observed in the location of the resonance frequencies associated with the peak impedance and transmissibility responses in the region of greatest human vibration sensitivity (4 to 8 Hz), with the majority being within 2 Hz of each other among all percentile groups. These findings indicate that the current vibration exposure standards reflect the frequency sensitivities of both females and males.

2. The impedance data, particularly when normalized for body weight, implies that there are specific differences between females and males in the distribution of mass, stiffness, and damping properties of those anatomical regions contributing to the observed vibration responses. The peak horizontal chest transmissibility tended to be higher in the males, while the peak vertical chest transmissibility tended to be higher in the females, strongly suggesting that the specific anatomical region of concern in defining differences between females and males is the upper torso. The subjective responses of the subjects support these findings. In addition, the impedance results

also suggest that leg resonance behavior is different between females and males. Leg transmissibility data analysis will be necessary to delineate the specific differences. Peak vertical head transmissibility and peak vertical spine (C_7) transmissibility were similar among the subjects.

3. As observed in previous studies, the cushions used in this study tended to increase the peak responses of those anatomical structures contributing to the resonance behavior observed between 4 and 8 Hz. The cushion with the lower stiffness and damping coefficients produced the highest response, although further analysis is required to delineate specific differences in cushion properties which contribute to increased vibration transmission. The increased vibration transmission may be of significance to females who already show higher vertical responses without the use of cushions.

4. For the test conditions and methods applied in this study, there were no significant differences in visual performance between females and males exposed to whole-body vibration. In general, vibration exposure produced greater visual performance degradation as compared to the no vibration condition with no specific differences observed relative to the frequency of exposure. The cushion producing the highest vertical chest transmissibility (Cushion A) was associated with the most significant visual performance degradation with increasing acceleration level.

5. Modeling techniques should be applied to the results of this study as a tool for quantifying specific differences in the mass, stiffness, and damping properties of those anatomical structures or regions contributing to the observed differences in the vibration response data.

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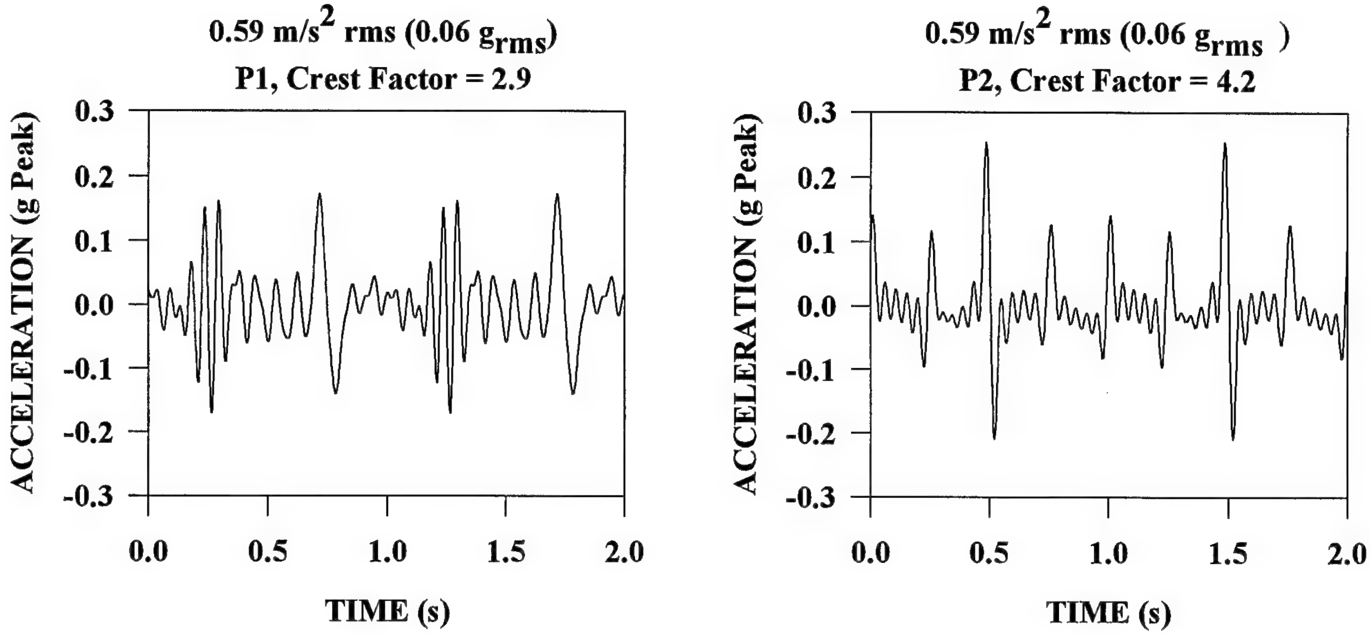


Figure 1 Sum-of-Sines Vibration Profiles

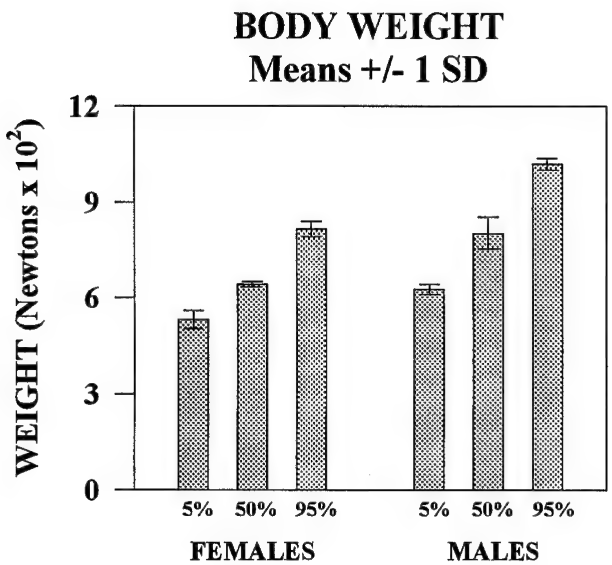


Figure 2 Mean Percentile Group Body Weights +/- One Standard Deviation

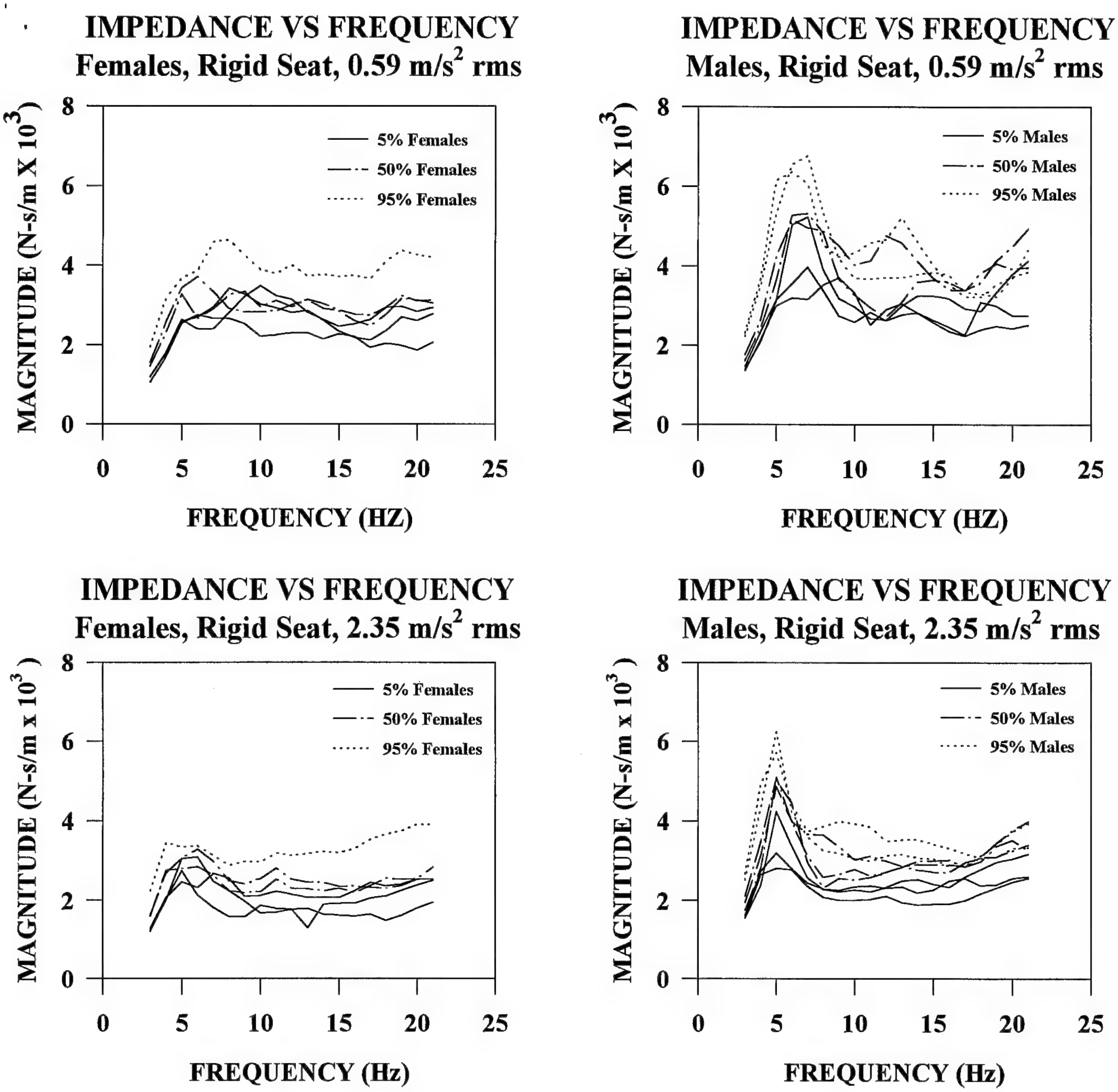


Figure 3 Driving-Point Mechanical Impedance Magnitude Frequency Responses

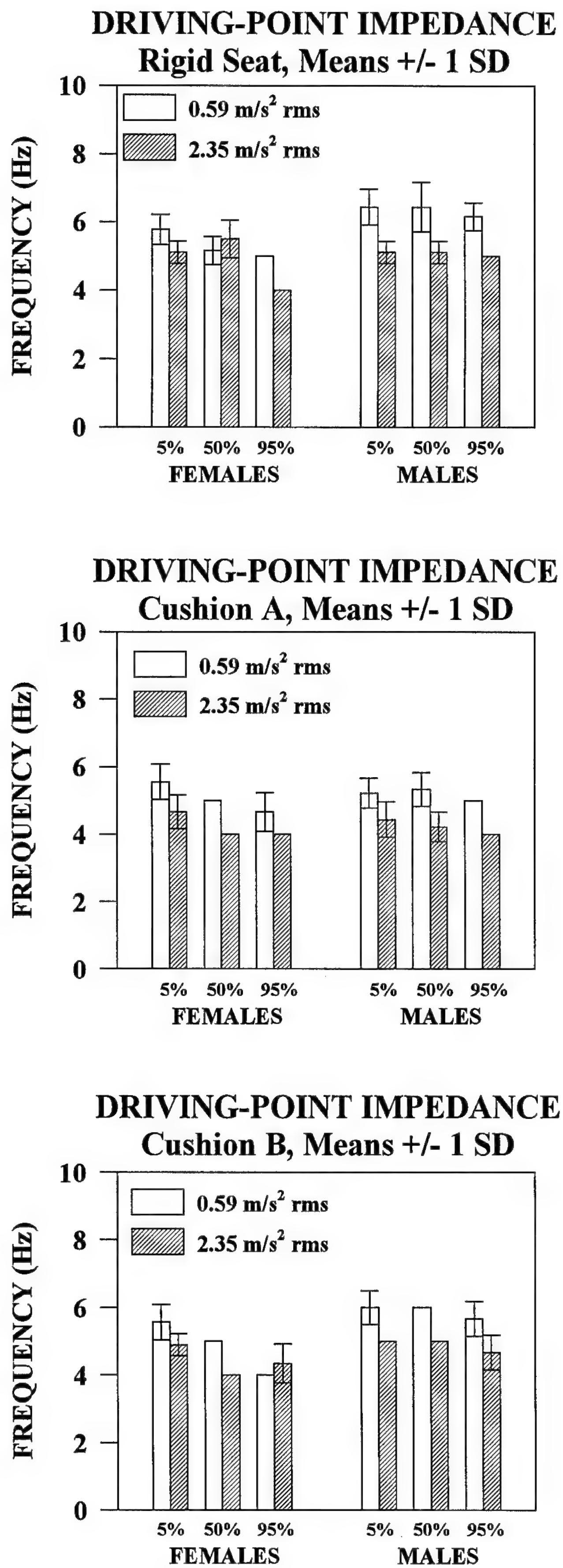


Figure 4 Primary Impedance Resonance Frequency Means +/- One Standard Deviation

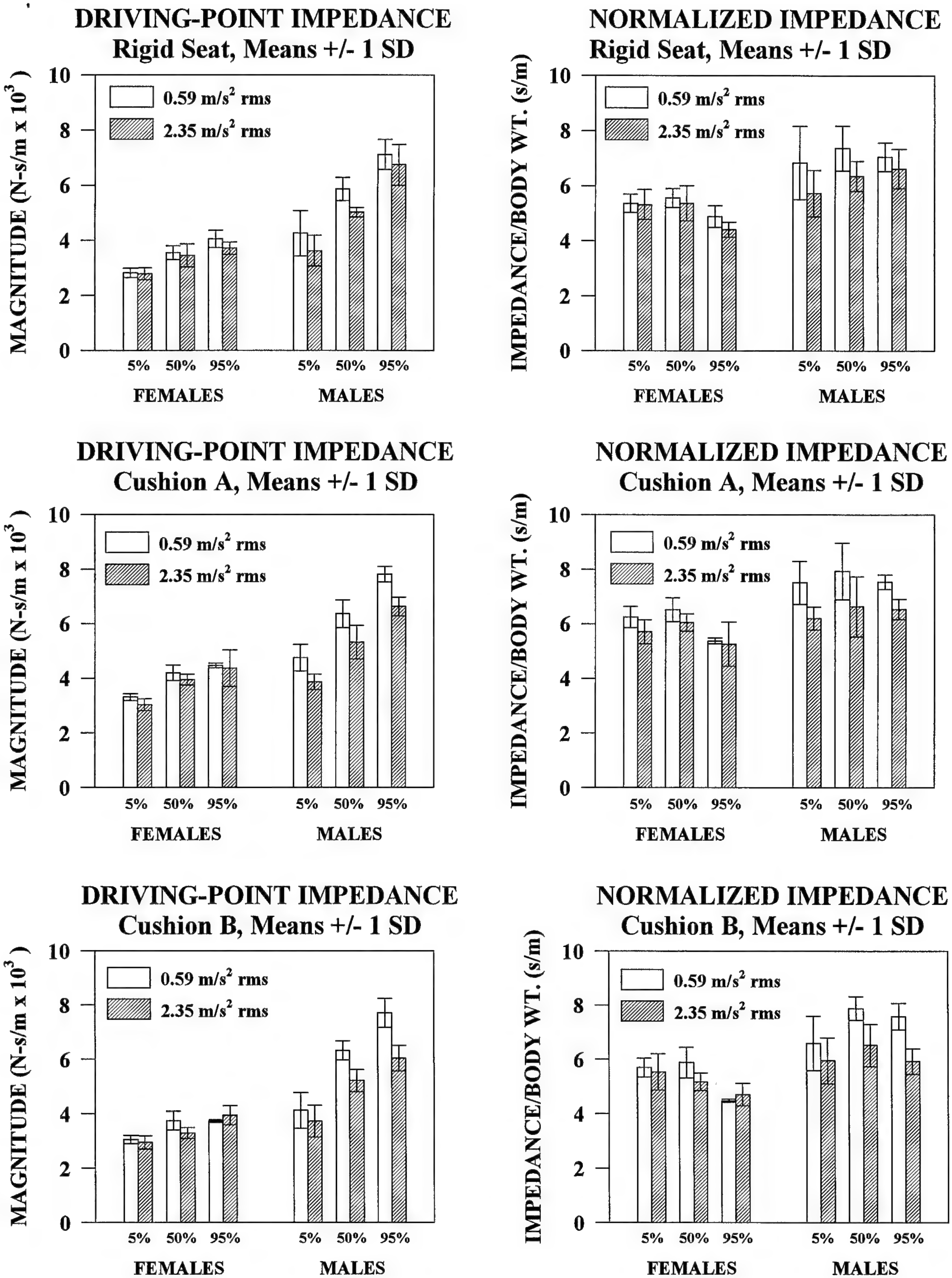
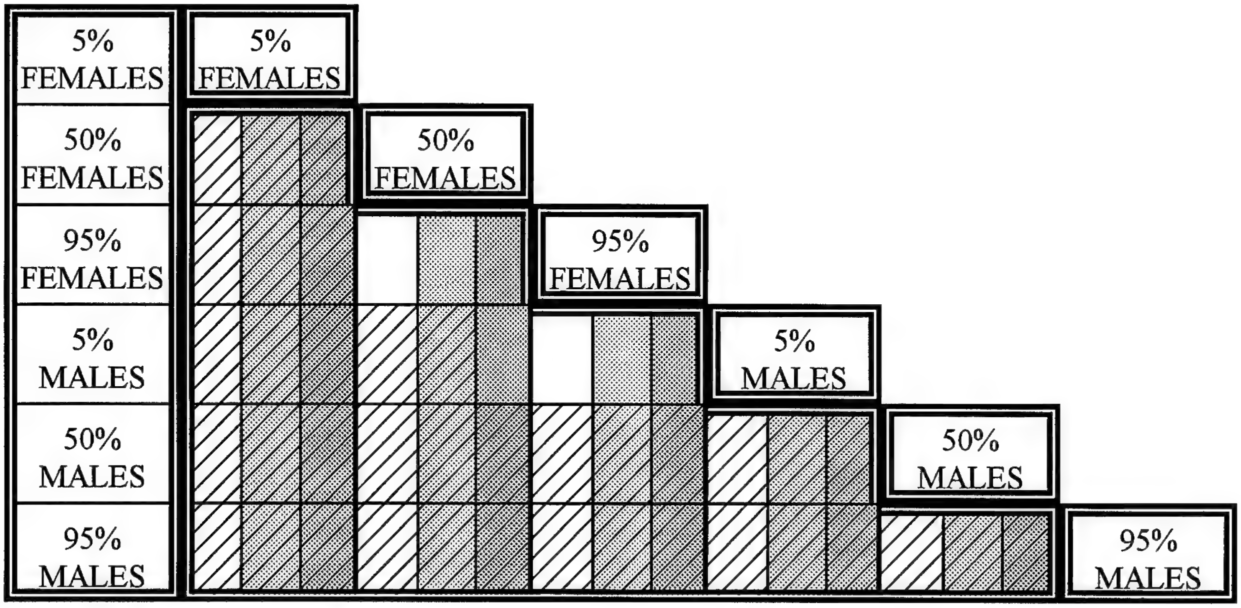
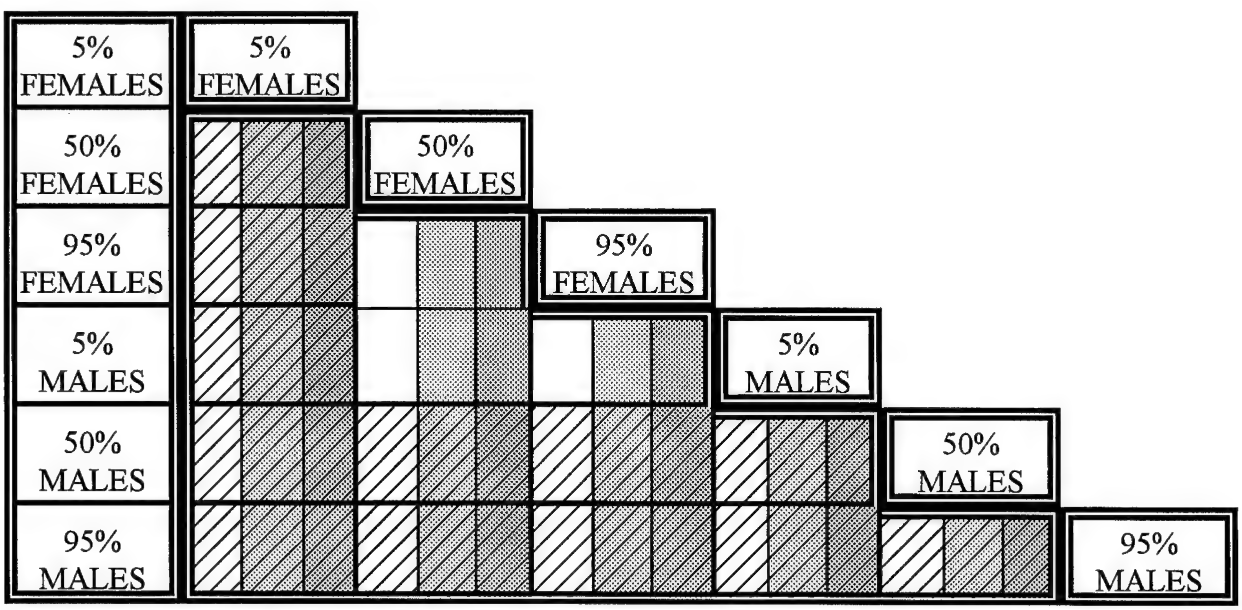


Figure 5 Primary Peak Impedance and Normalized Peak Impedance Magnitude Means +/- One Standard Deviation



Acceleration = 0.59 m/s^2 rms



Acceleration = 2.35 m/s^2 rms

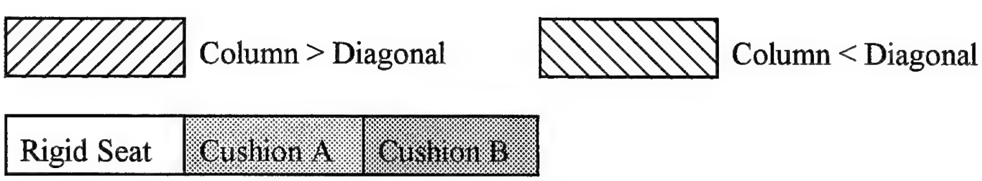
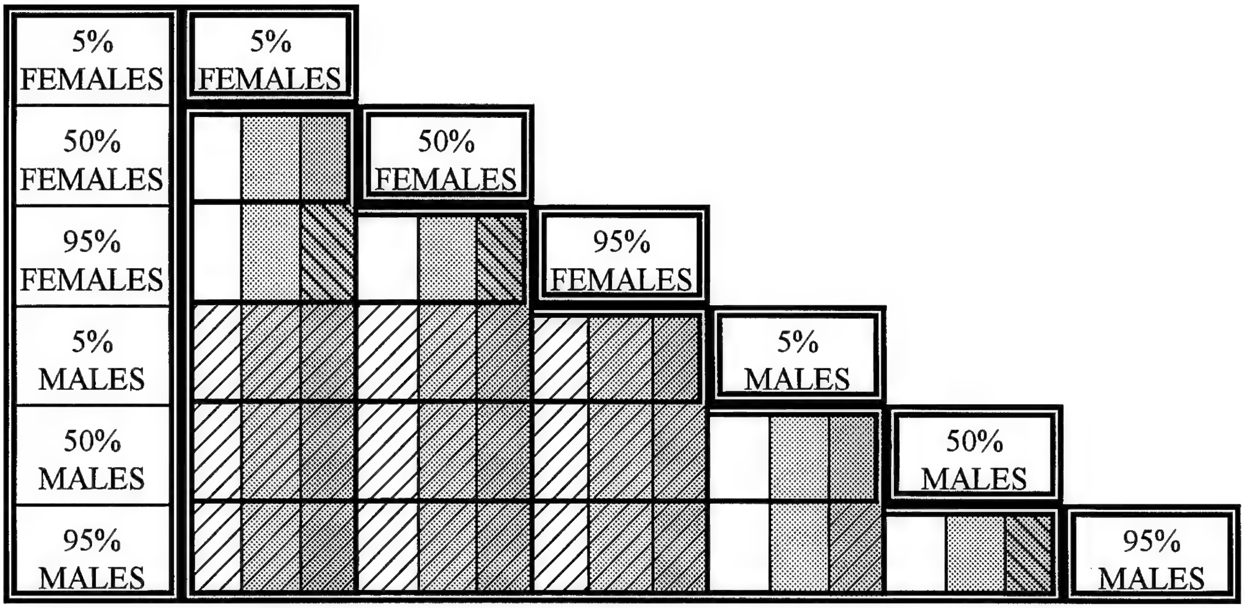
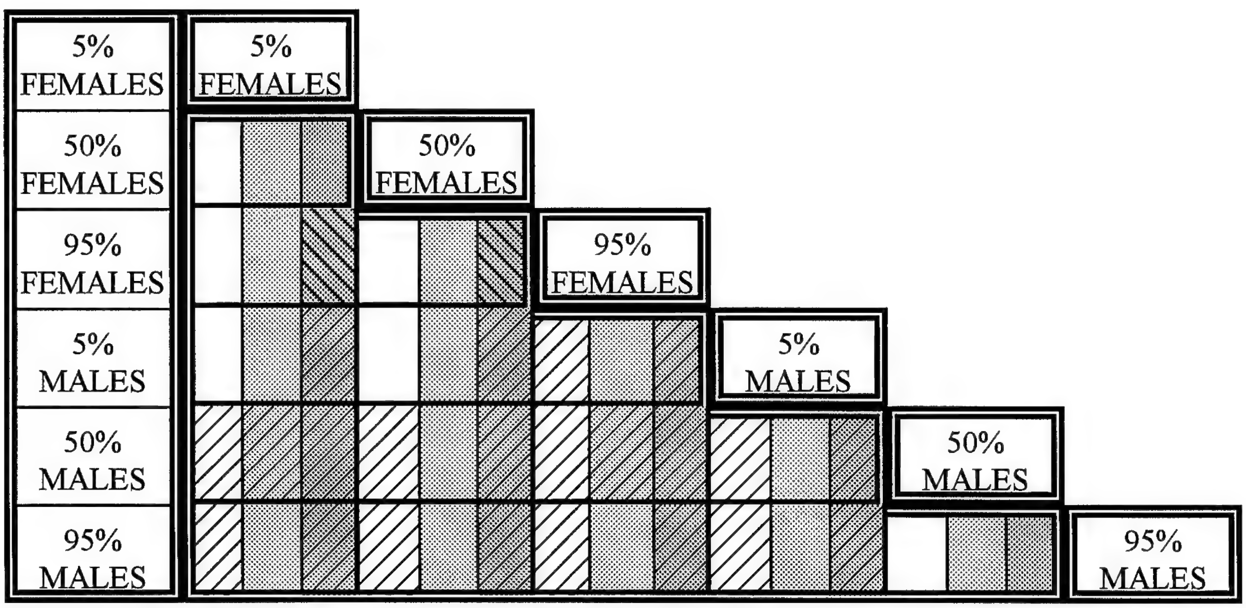


Figure 6 Summary of Statistical Results - Primary Peak Impedance



Acceleration = 0.59 m/s^2 rms



Acceleration = 2.35 m/s^2 rms

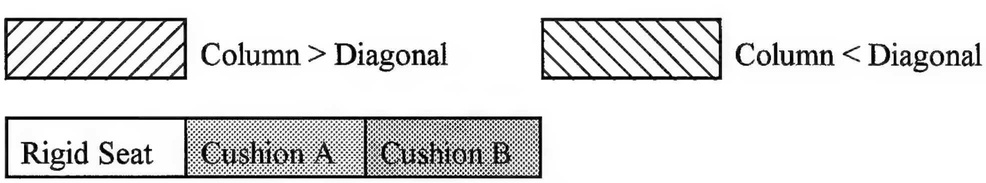


Figure 7 Summary of Statistical Results - Normalized Peak Impedance

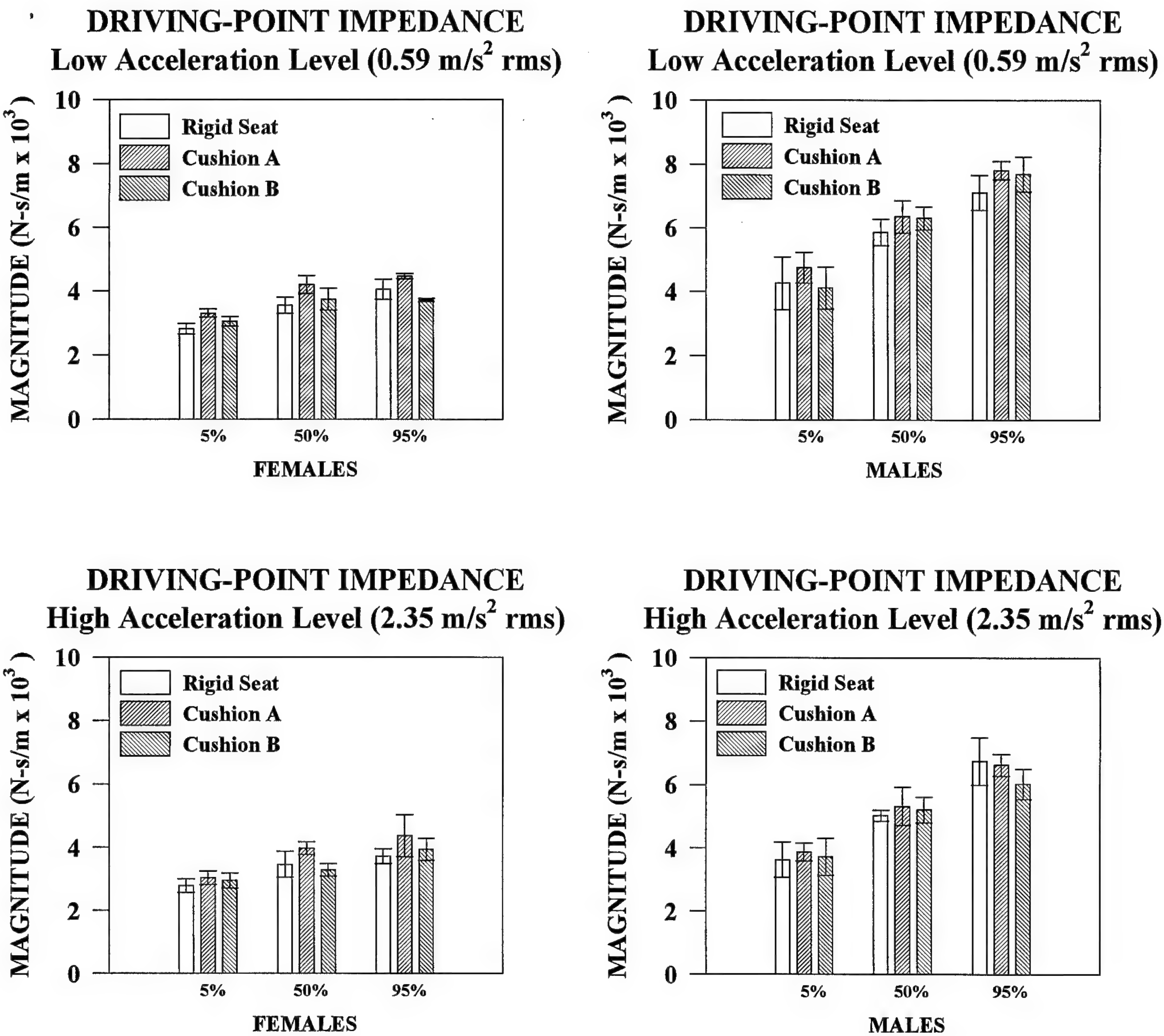


Figure 8 Primary Peak Impedance Magnitude Means +/- One Standard Deviation - Seat Configuration Effects

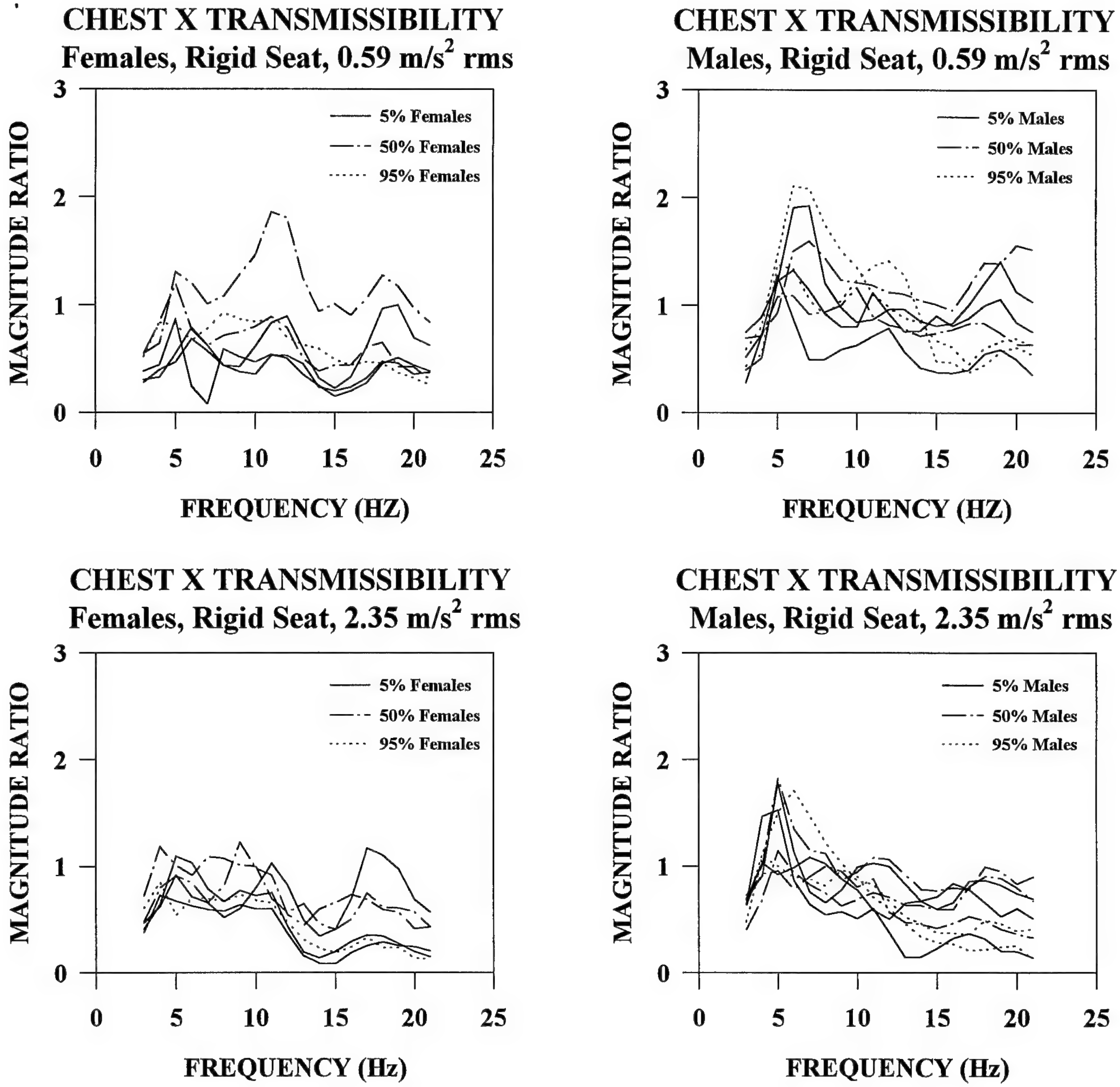


Figure 9 Horizontal (X) Chest Transmissibility Magnitude Frequency Responses

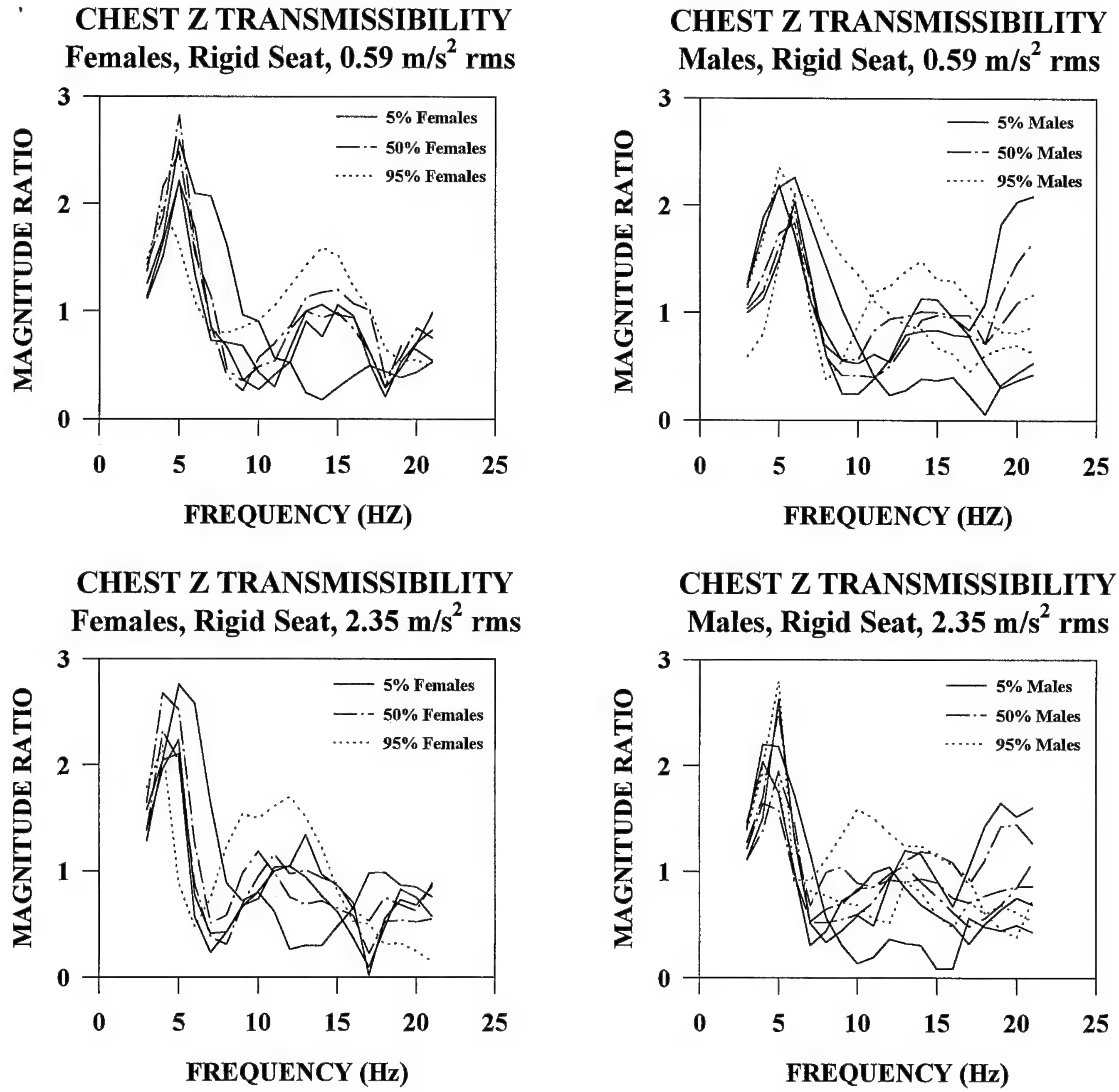


Figure 10 Vertical (Z) Chest Transmissibility Magnitude Frequency Responses

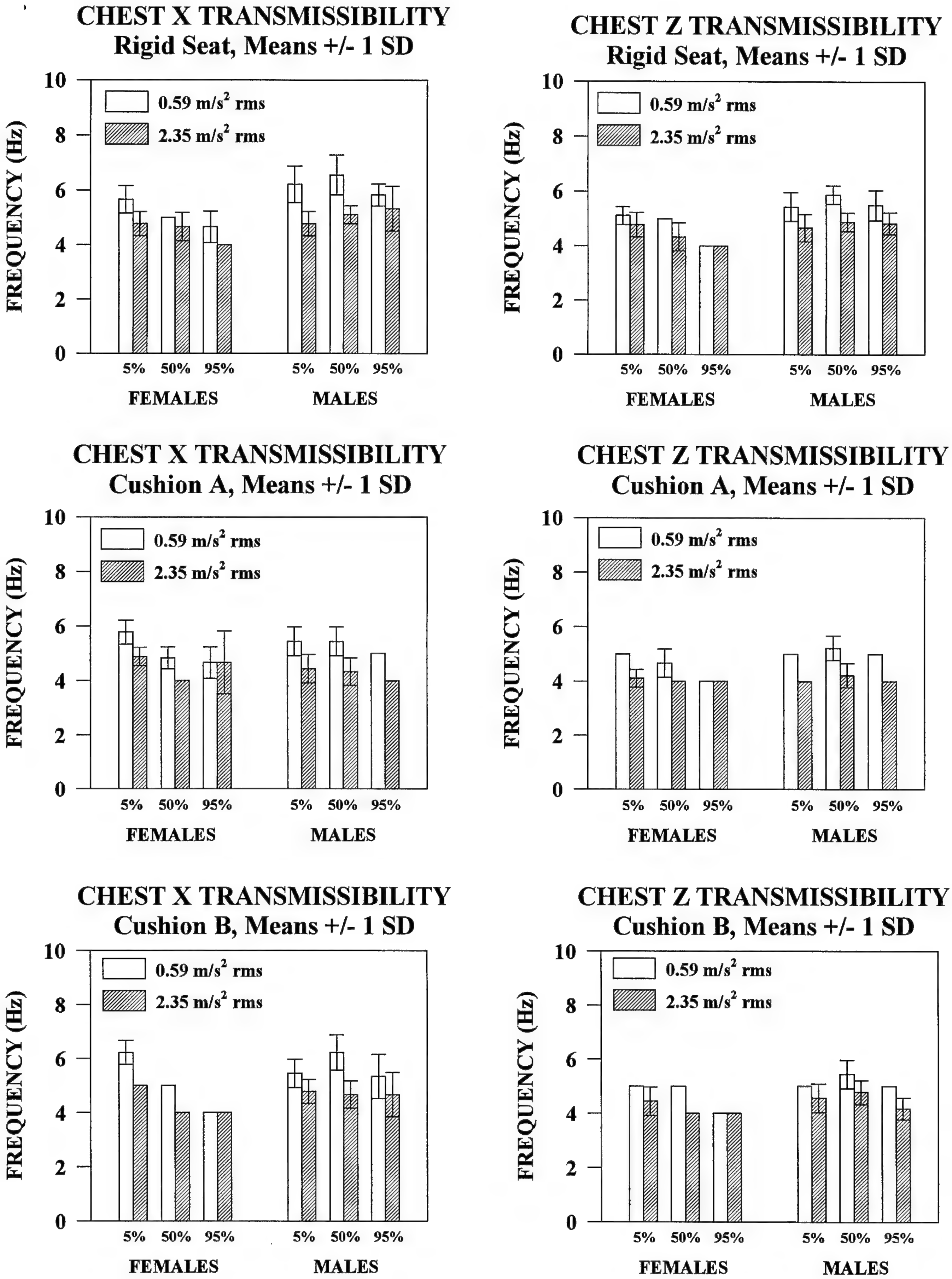


Figure 11 Primary Horizontal (X) and Vertical (Z) Chest Transmissibilities Resonance Frequency Means +/- One Standard Deviation

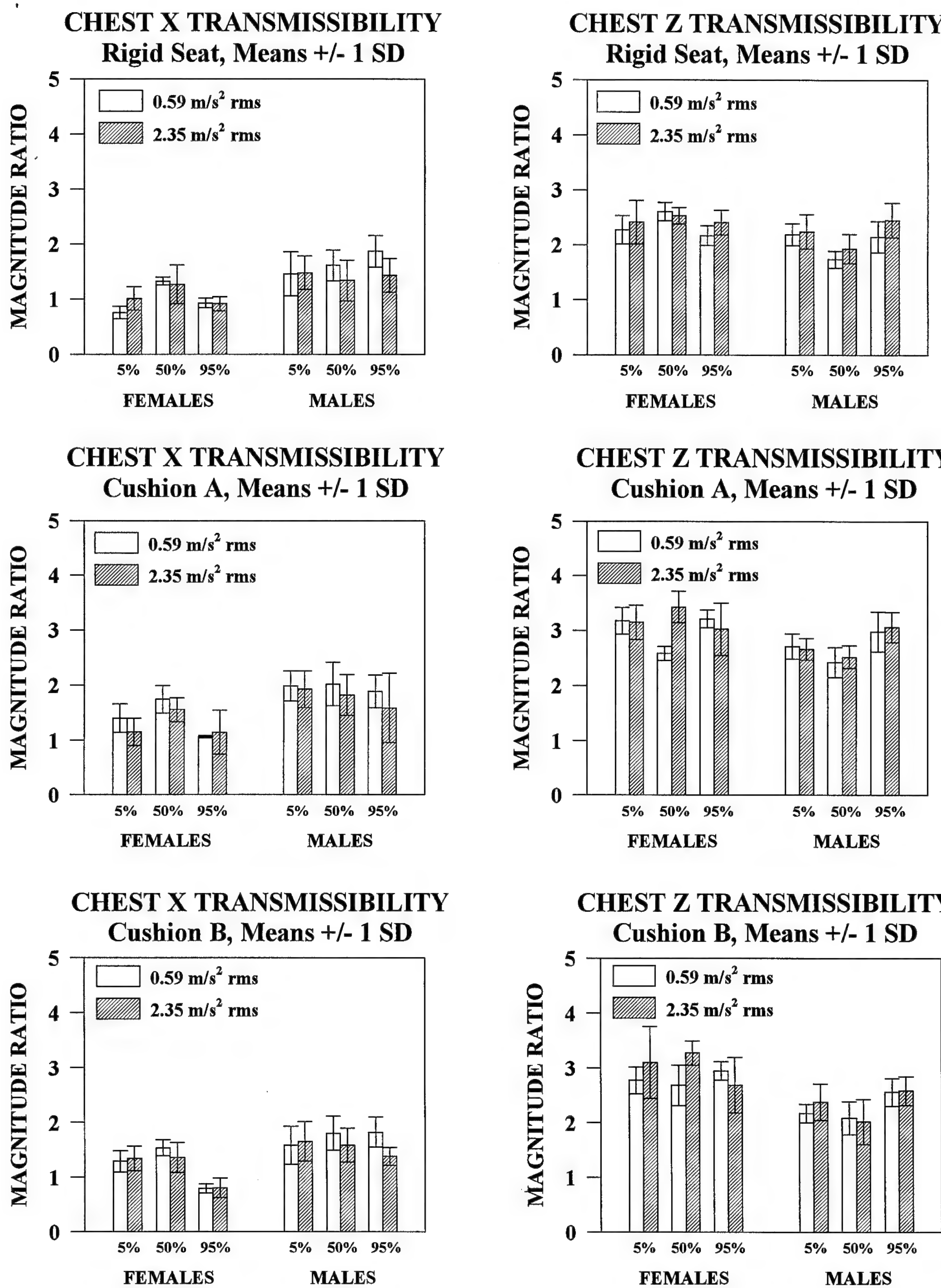
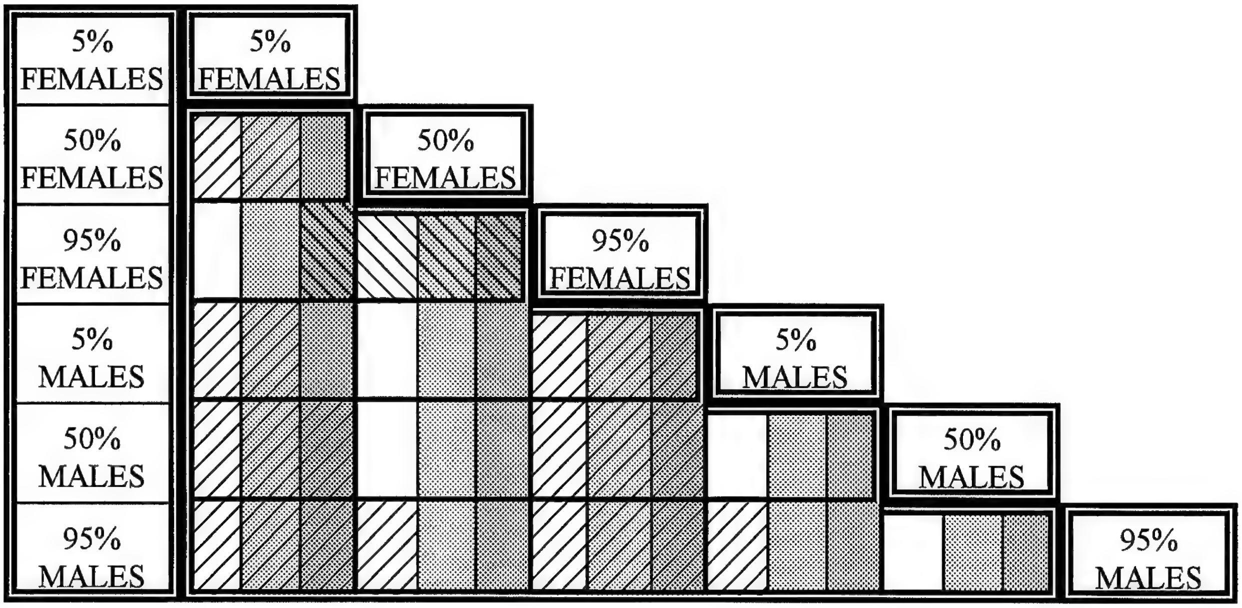
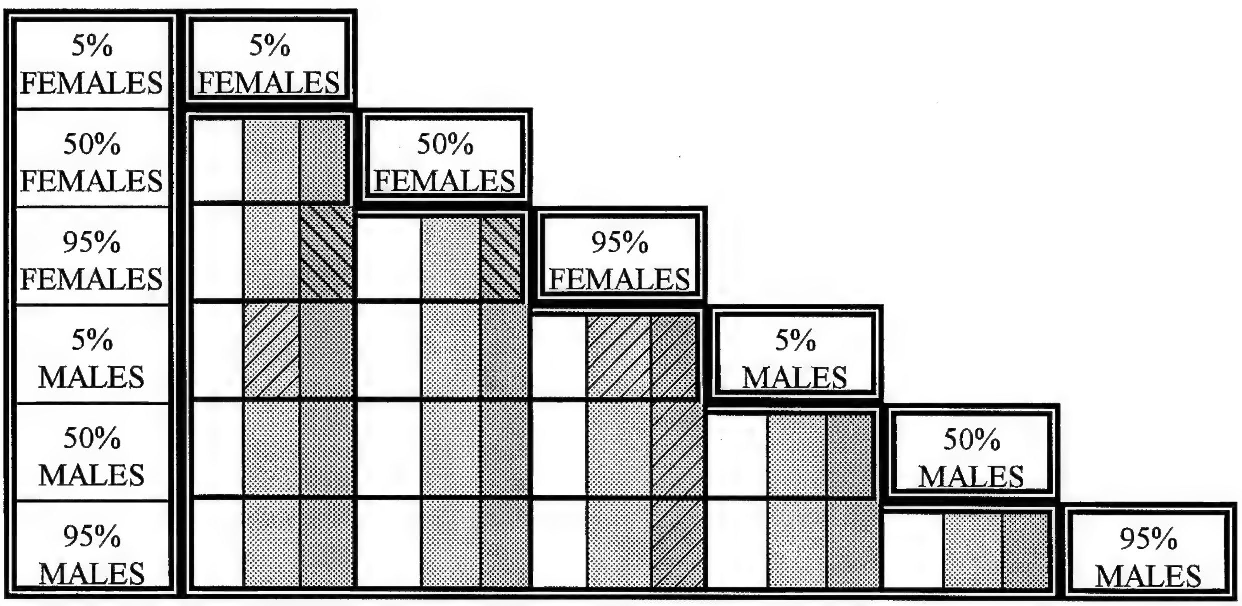


Figure 12 Primary Peak Horizontal (X) and Vertical (Z) Chest Transmissibilities Means +/- One Standard Deviation



Acceleration = 0.59 m/s^2 rms



Acceleration = 2.35 m/s^2 rms

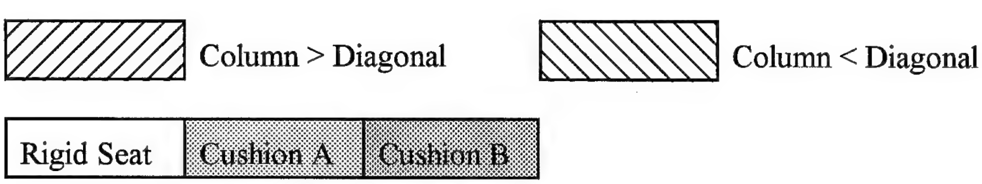


Figure 13 Summary of Statistical Results - Peak Horizontal (X) Chest Transmissibility

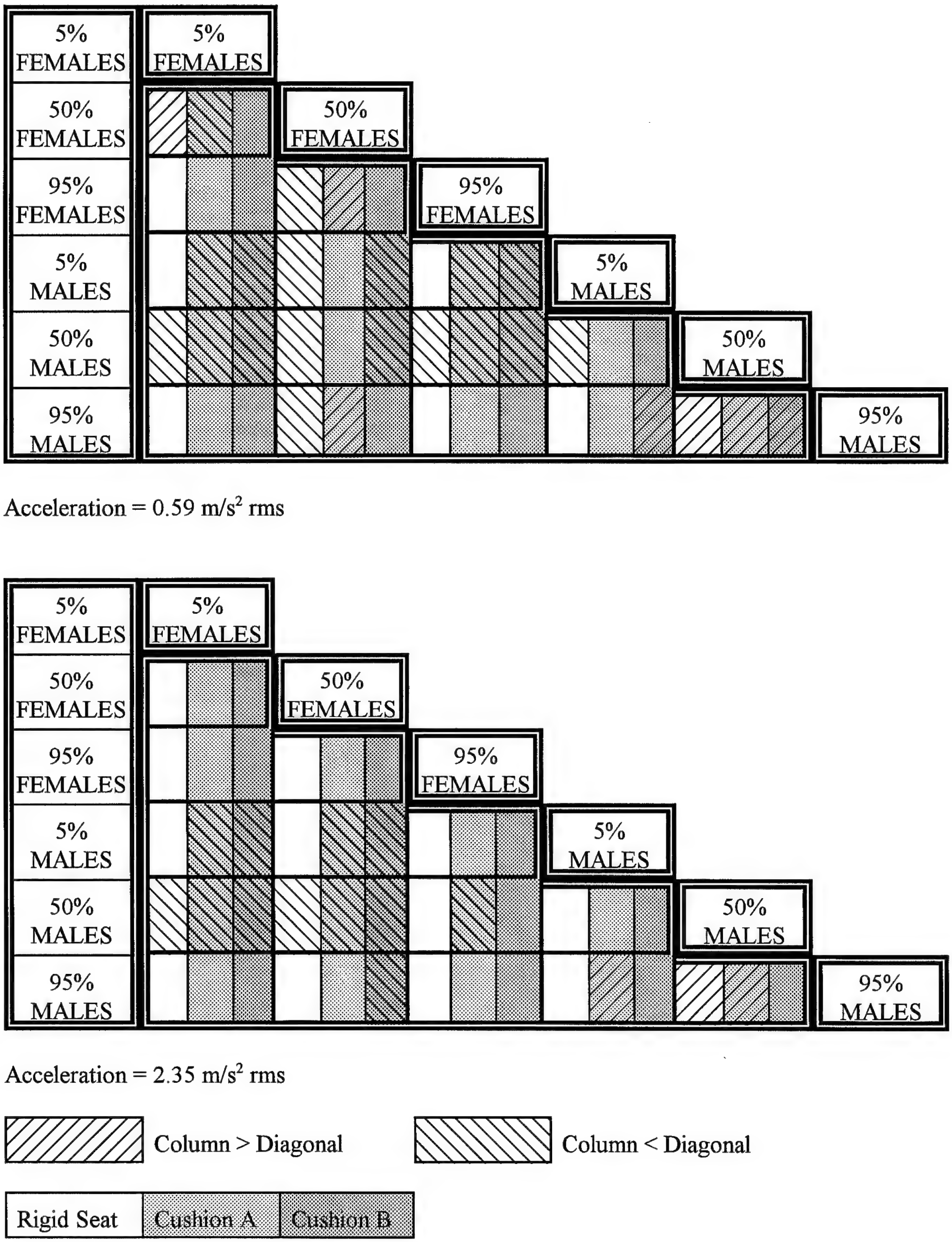


Figure 14 Summary of Statistical Results - Peak Vertical (Z) Chest Transmissibility

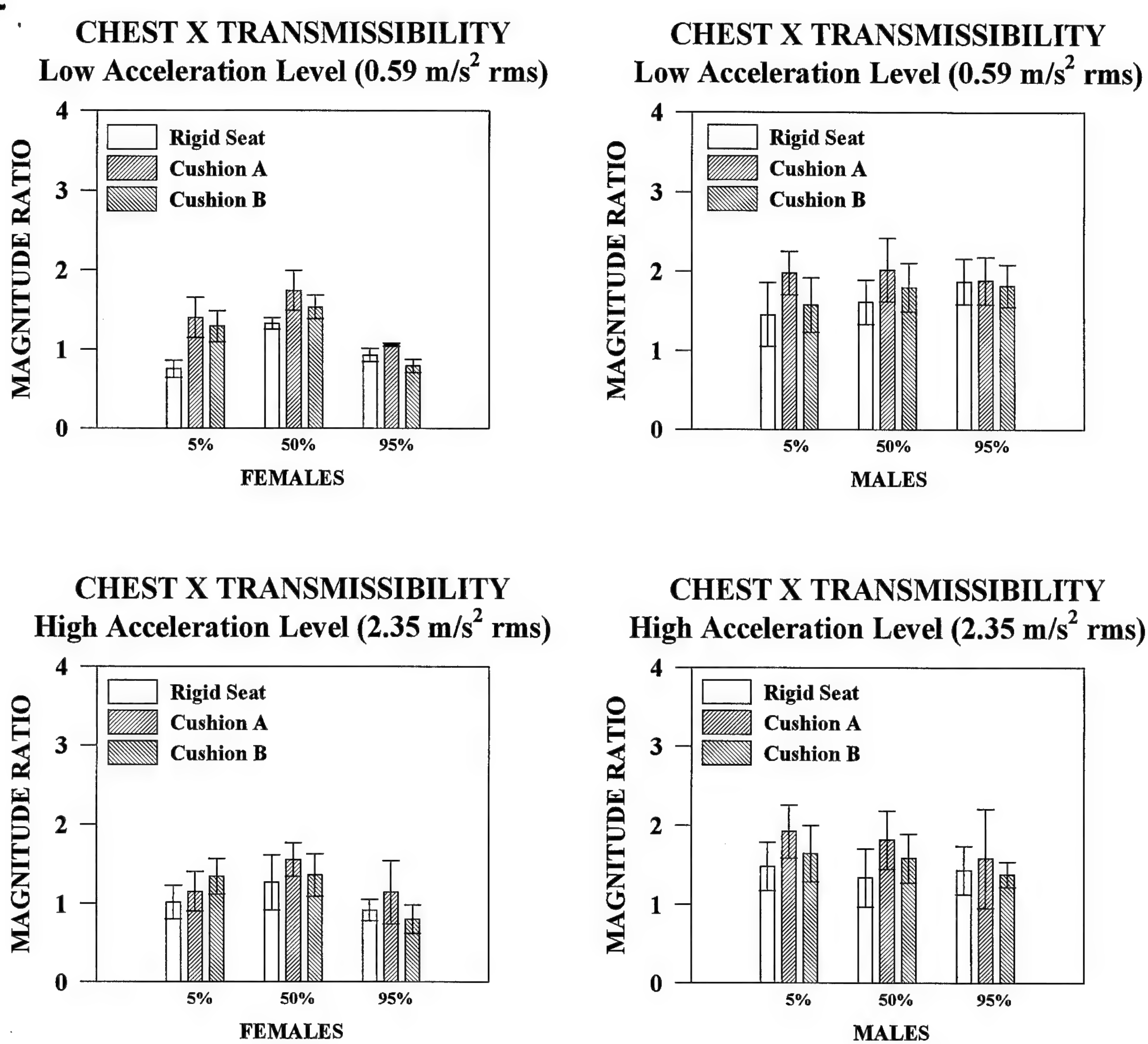


Figure 15 Primary Peak Horizontal (X) Chest Transmissibility Means +/- One Standard Deviation - Seat Configuration Effects

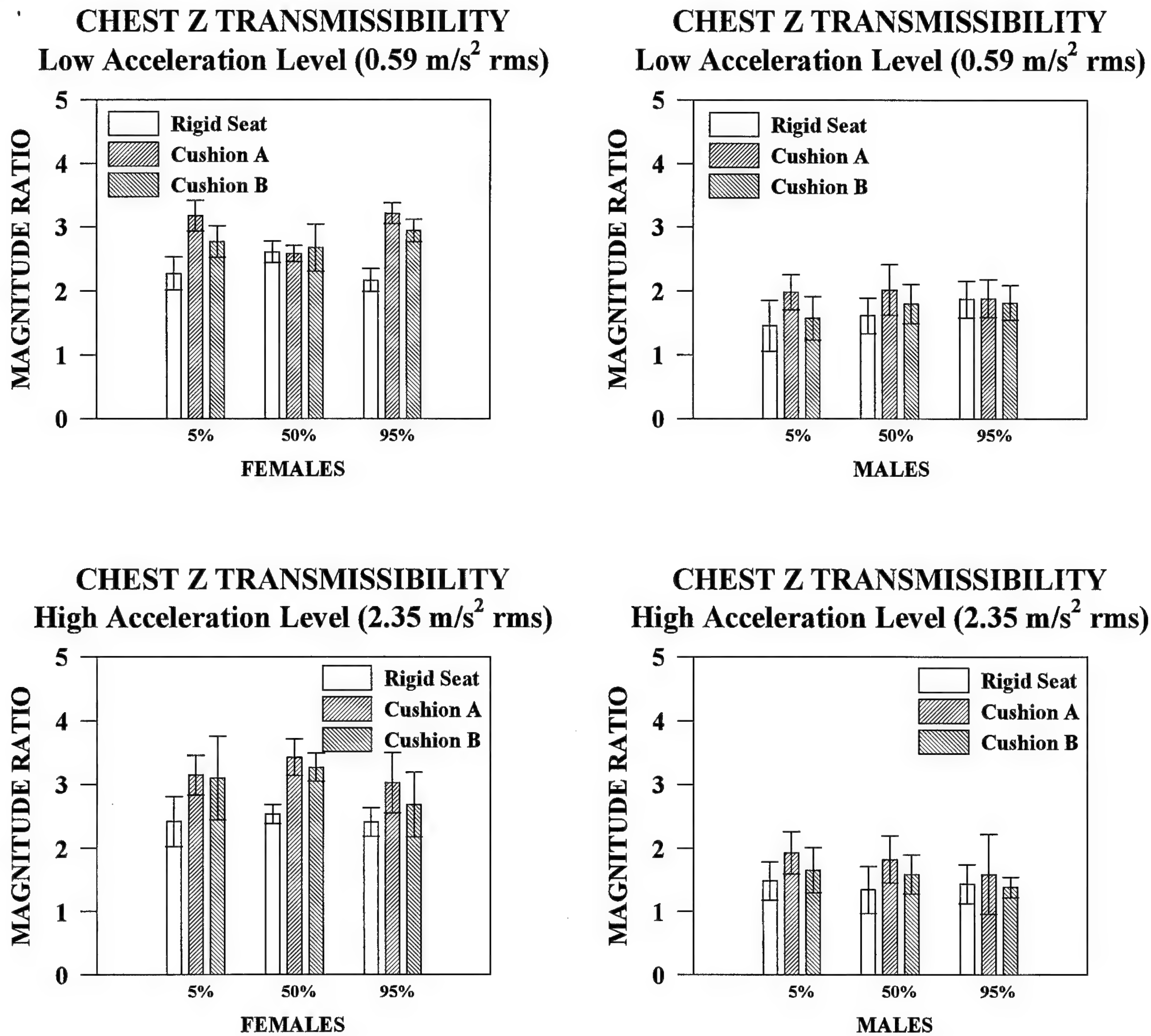


Figure 16 Primary Peak Vertical (Z) Chest Transmissibility Means +/- One Standard Deviation - Seat Configuration Effects

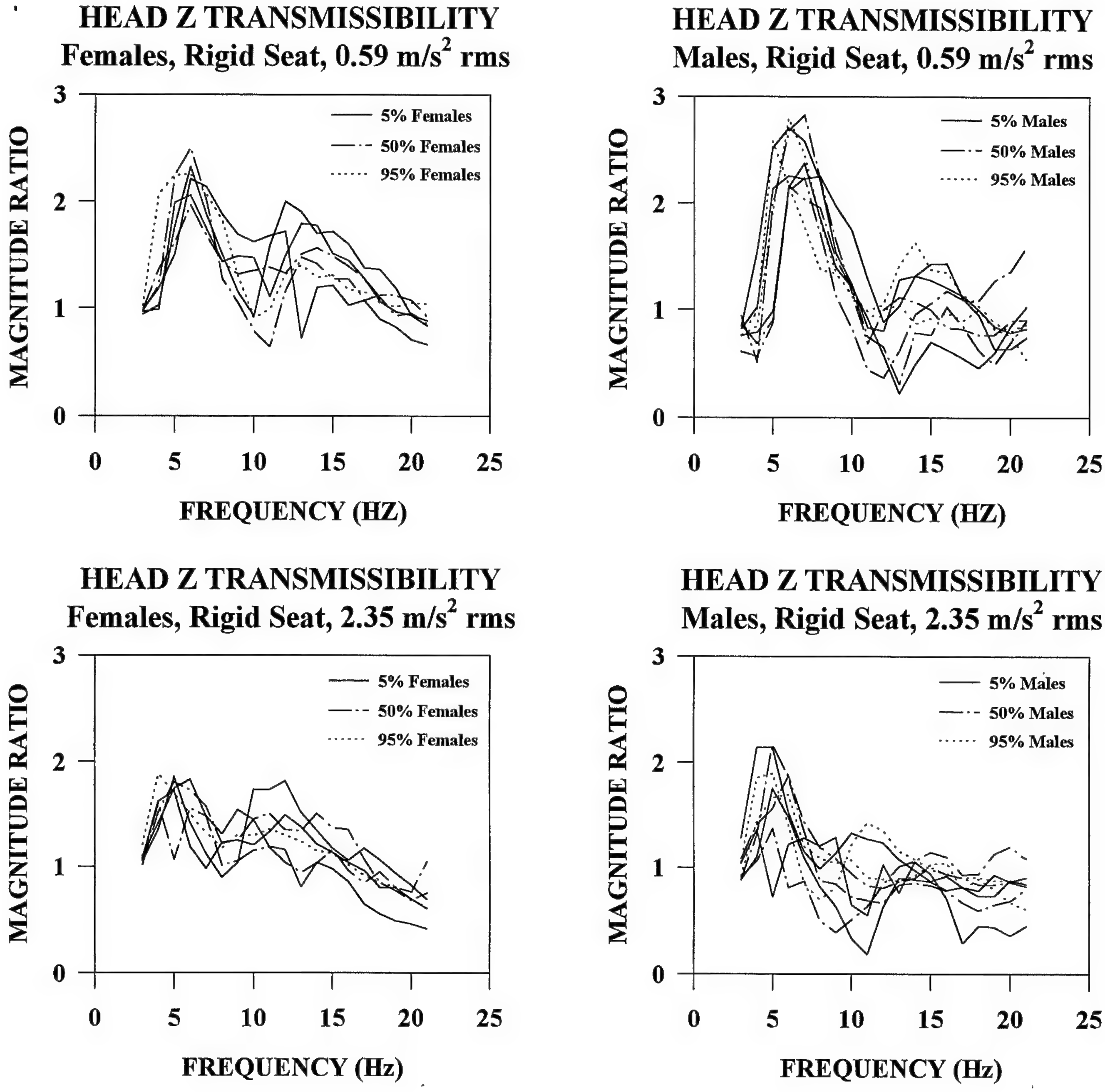
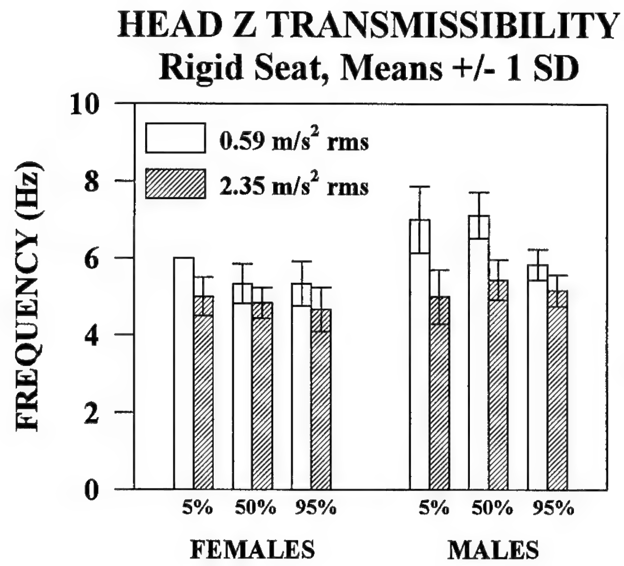
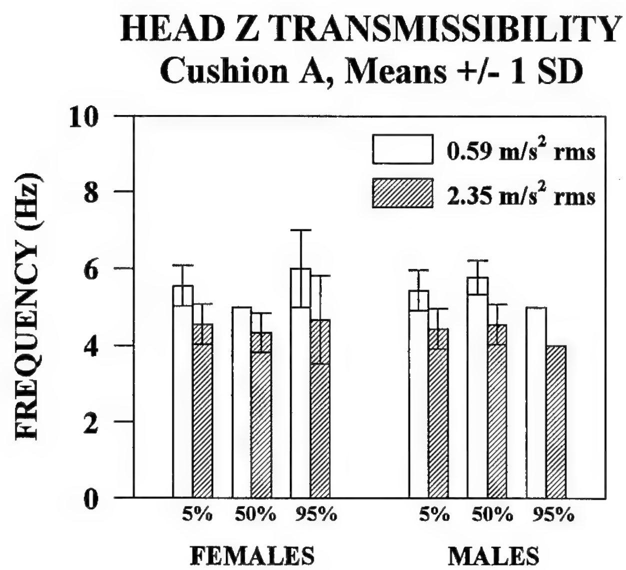


Figure 17 Vertical (Z) Head Transmissibility Magnitude Frequency Responses





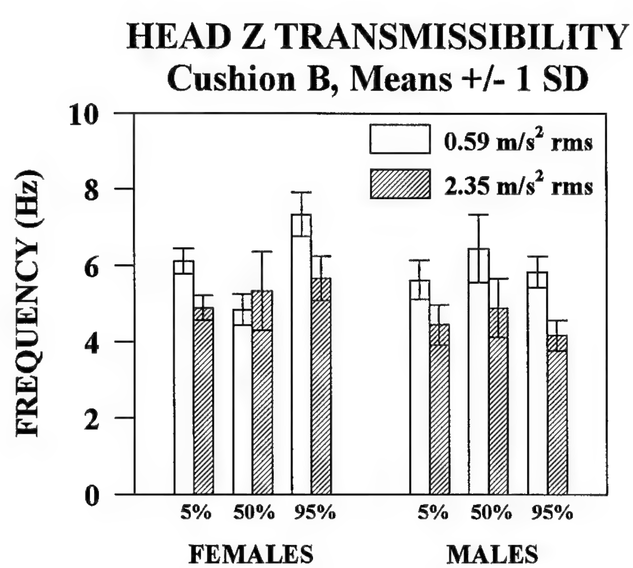
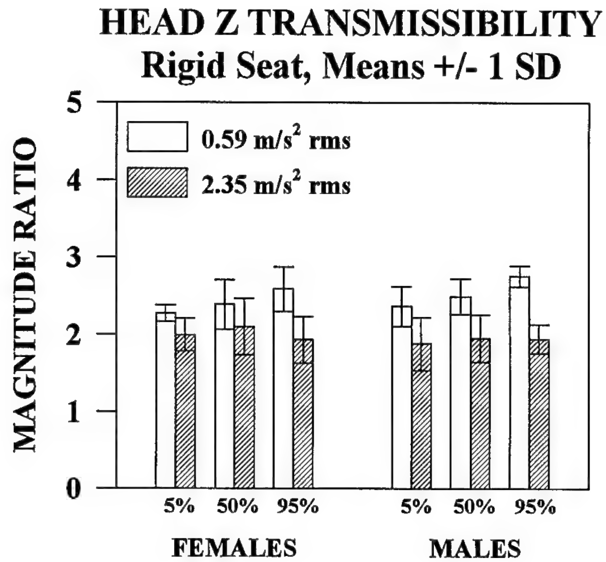
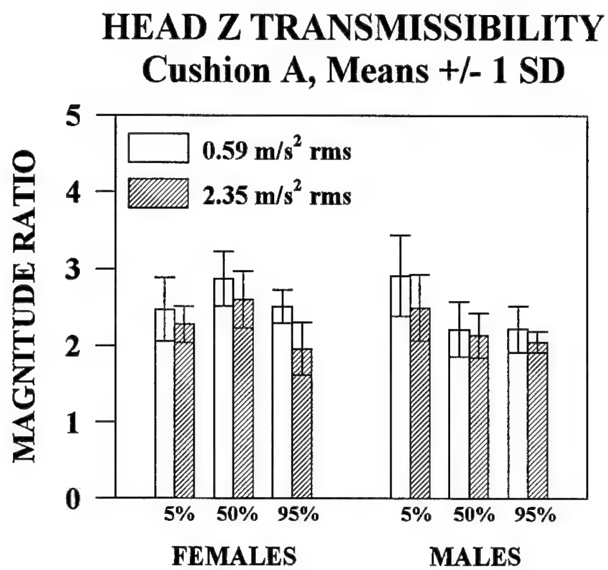


Figure 18 Primary Vertical (Z) Head Transmissibility Resonance Frequency Means +/- One Standard Deviation





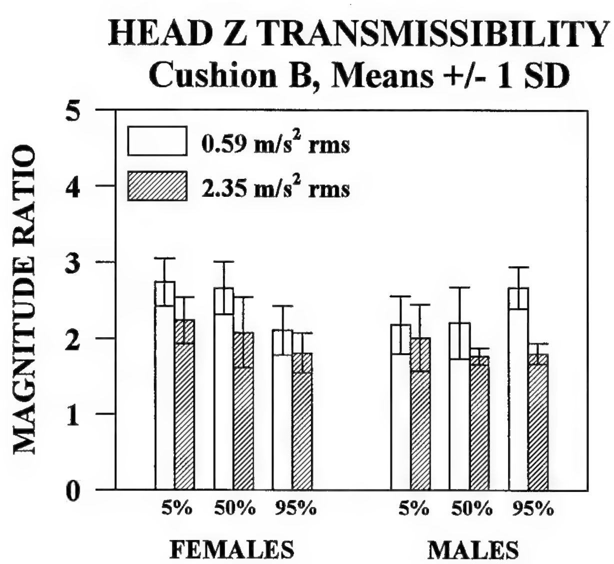
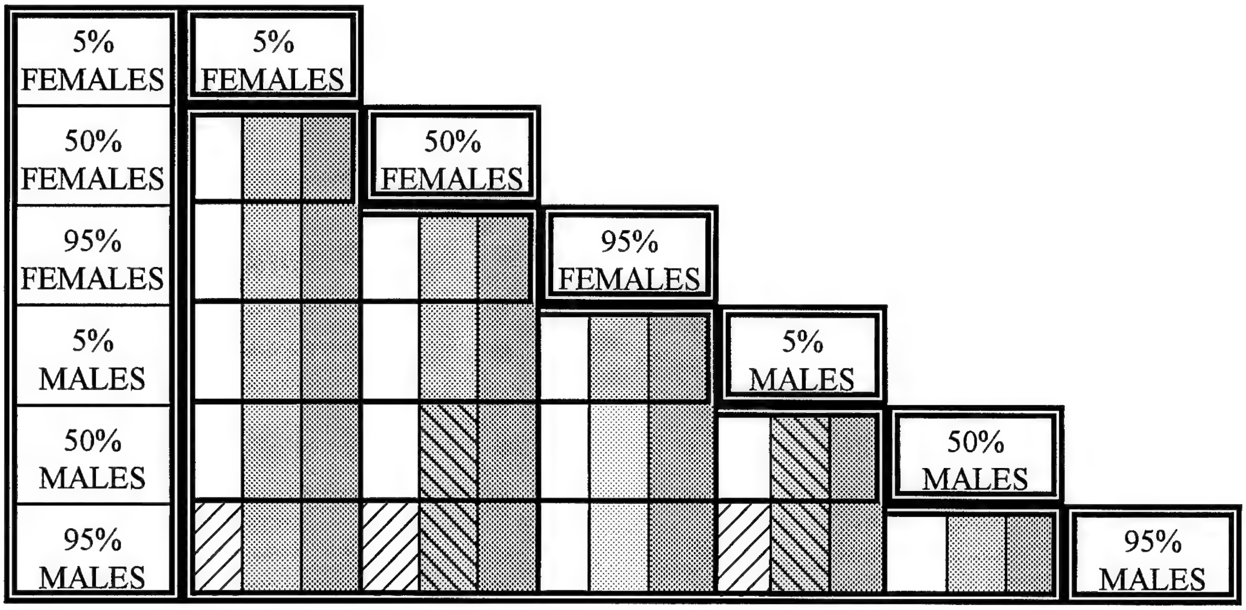
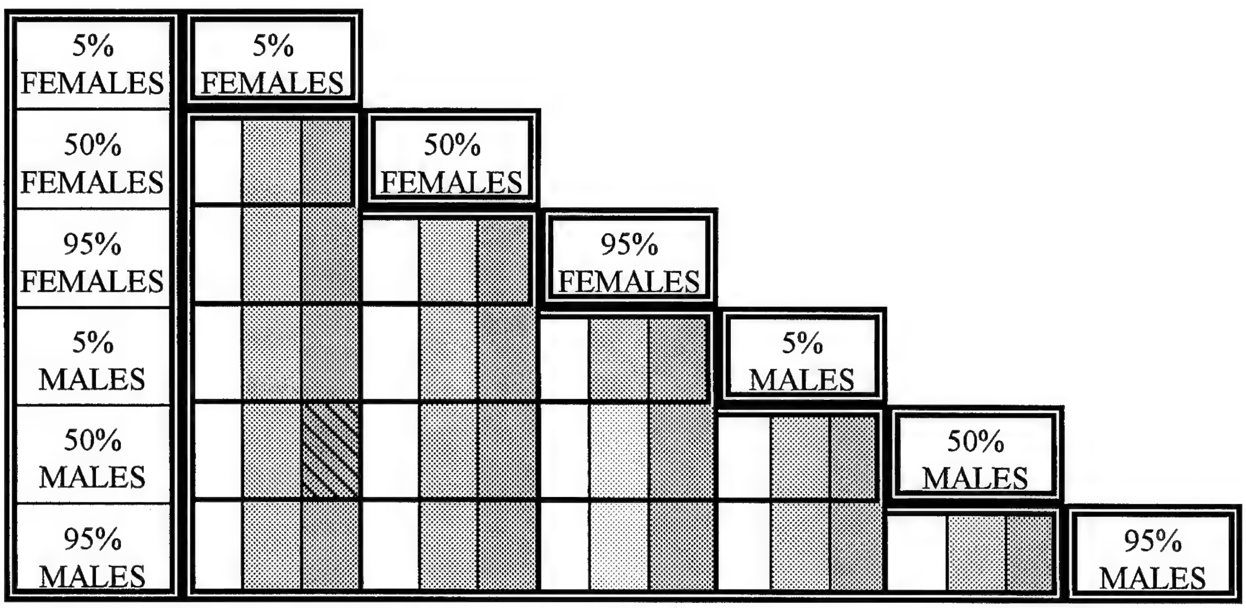


Figure 19 Primary Peak Vertical (Z) Head Transmissibility Means +/- One Standard Deviation



Acceleration = 0.59 m/s^2 rms



Acceleration = 2.35 m/s^2 rms

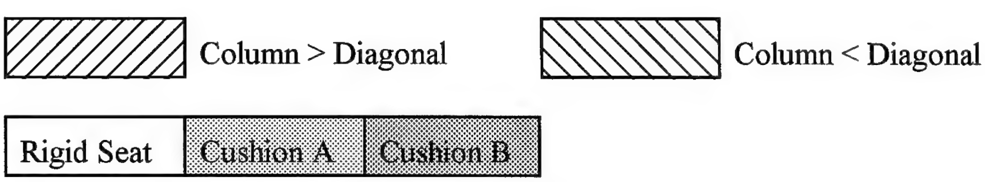


Figure 20 Summary of Statistical Results - Peak Vertical (Z) Head Transmissibility

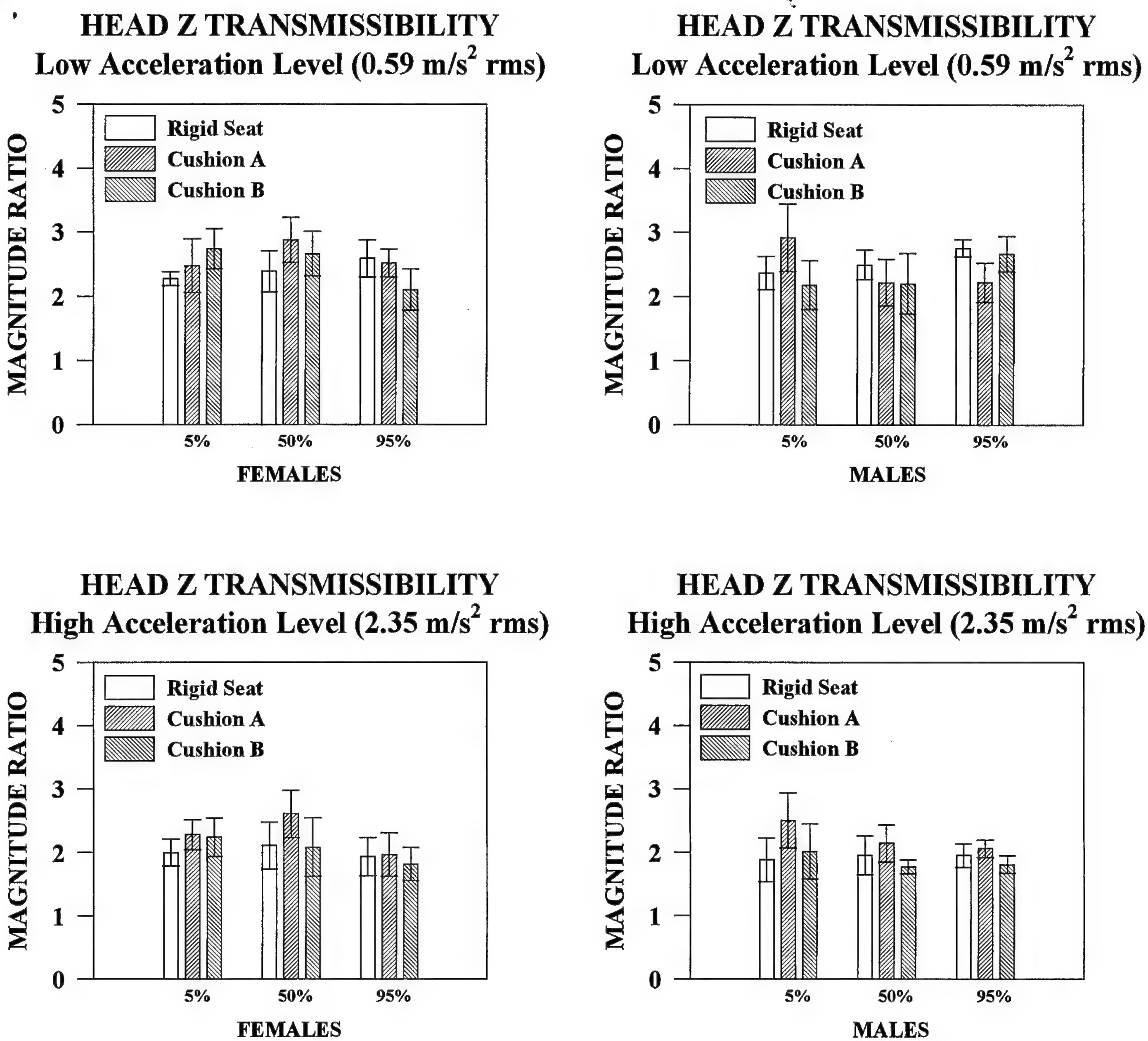


Figure 21 Primary Peak Vertical (Z) Head Transmissibility Means +/- One Standard Deviation - Seat Configuration Effects

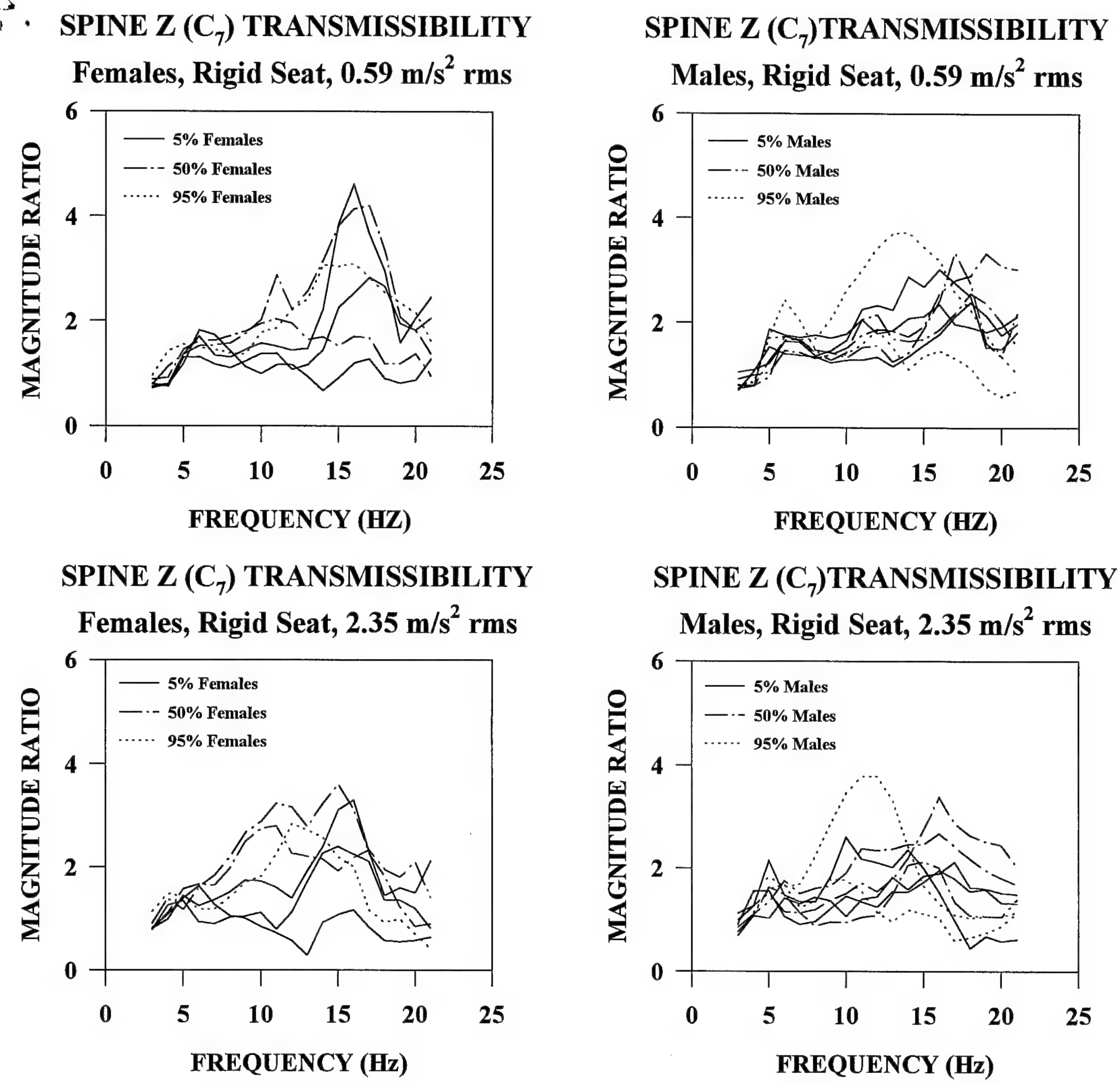


Figure 22 Vertical (Z) Spine (C_7) Transmissibility Magnitude Frequency Responses

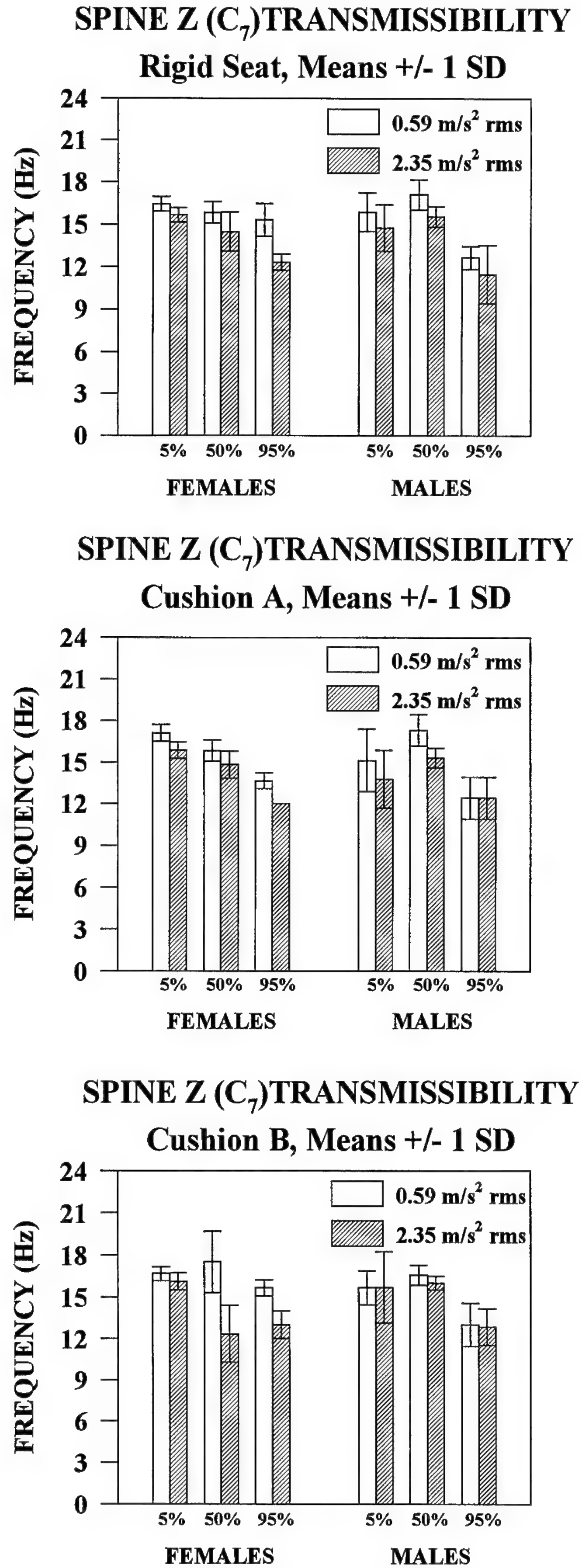


Figure 23 Primary Vertical (Z) Spine (C_7) Transmissibility Resonance Frequency Means +/- One Standard Deviation

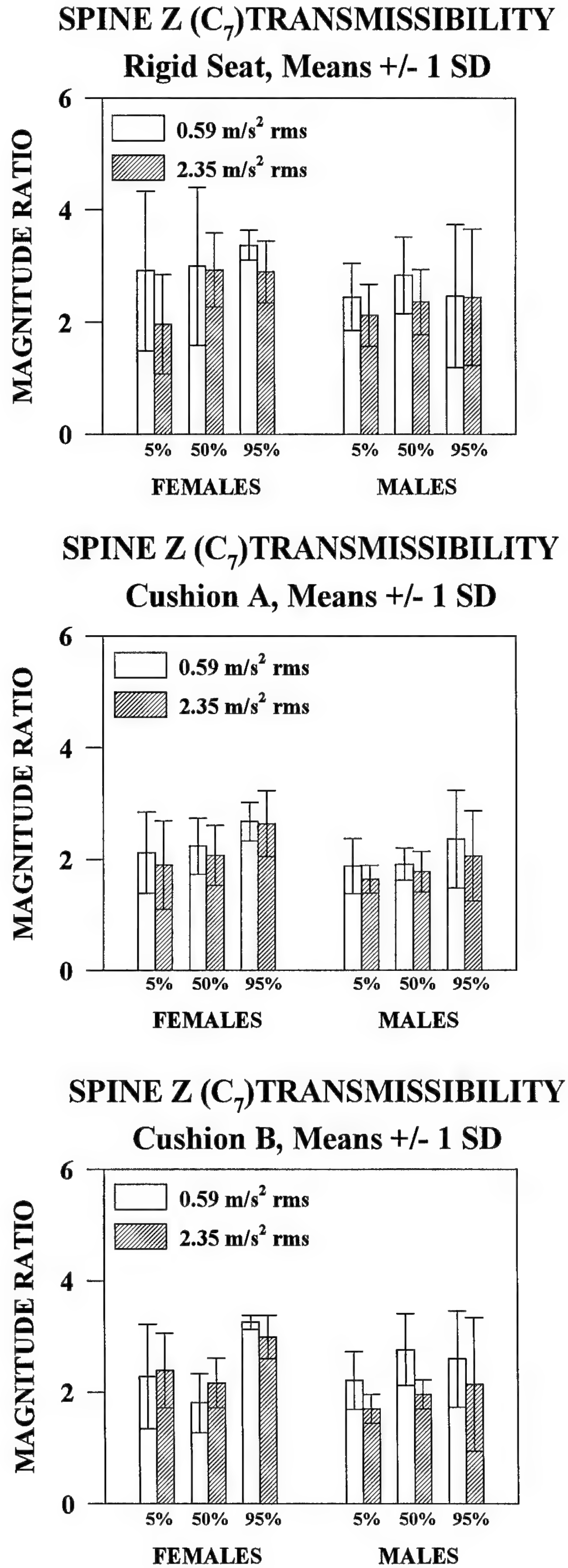


Figure 24 Primary Peak Vertical (Z) Spine (C_7) Transmissibility Means +/- One Standard Deviation

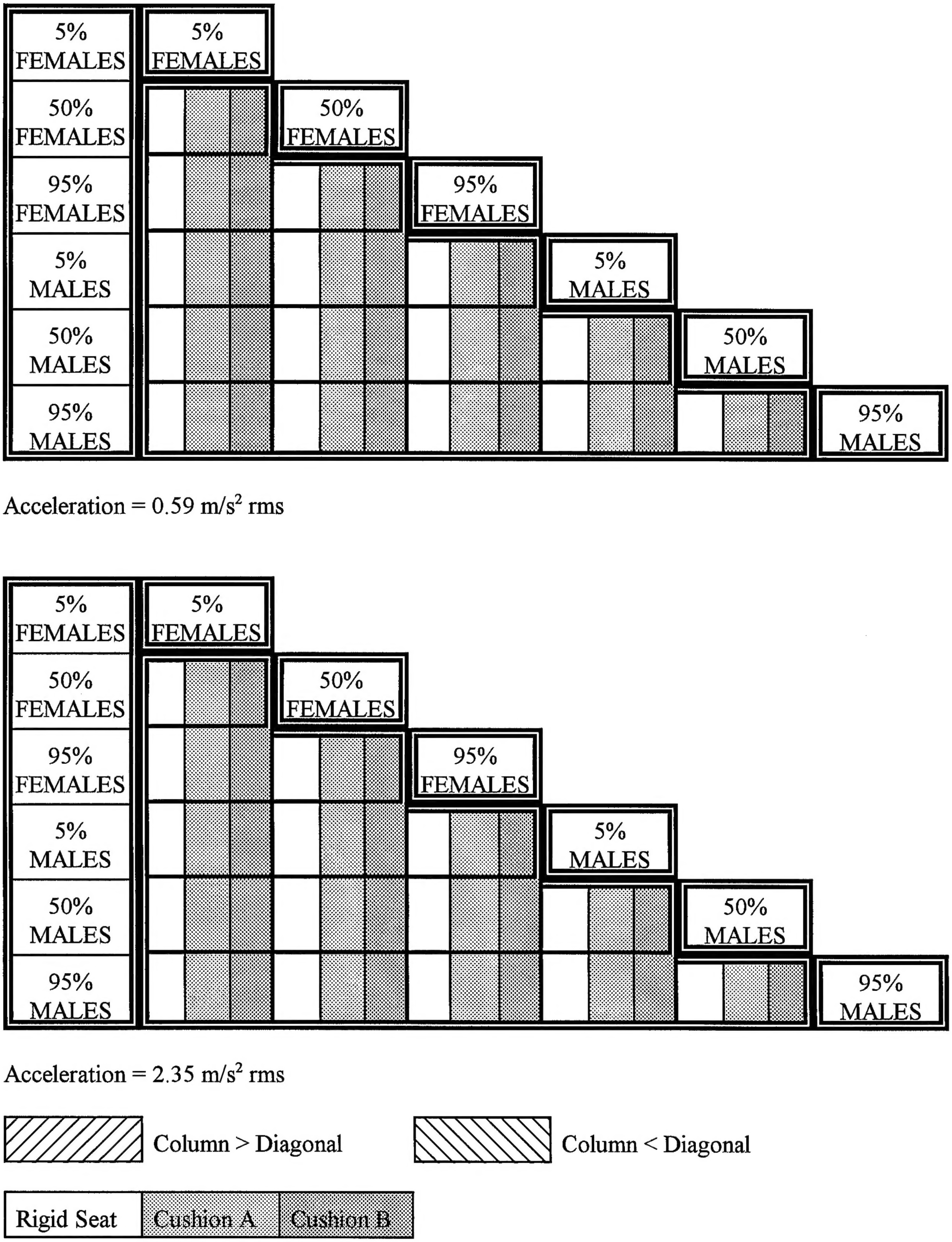


Figure 25 Summary of Statistical Results - Peak Vertical (Z) Spine (C_7) Transmissibility

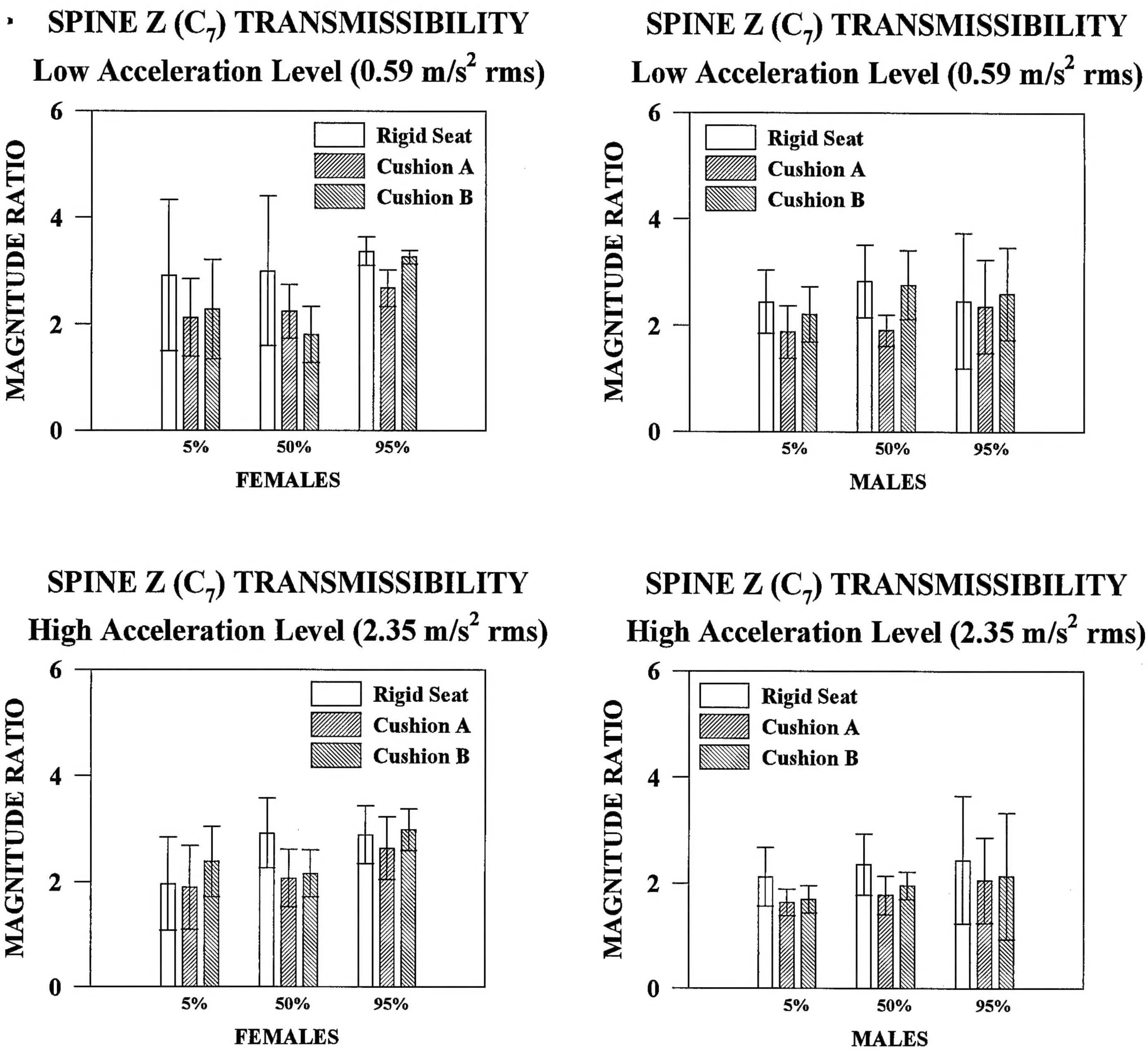


Figure 26 Primary Peak Vertical (Z) Spine (C_7) Transmissibility Means +/- One Standard Deviation - Seat Configuration Effects

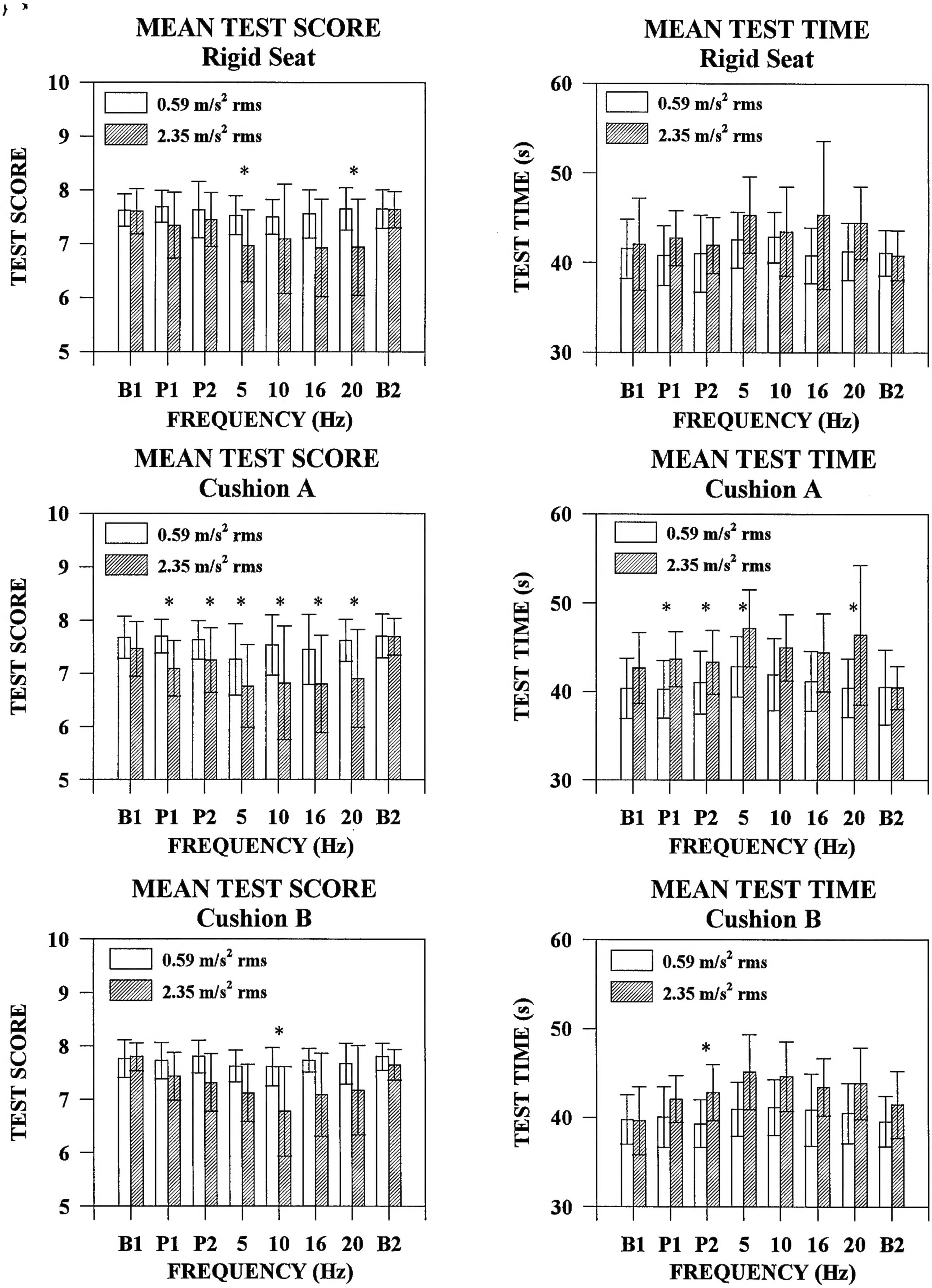


Figure 27 Mean Visual Acuity Test Scores and Test Times +/- One Standard Deviation (B1, B2=Baselines; P1, P2=Sum-of-Sines)

1. The following is a listing of all publications and presentations associated with this study which have occurred since 1 December 1994:

Smith, S. D., "Resonance Behavior of Females and Males Exposed to Whole-Body Vibration," Proceedings of the Fifteenth Southern Biomedical Engineering Conference, University of Dayton, Dayton OH, 29-31 March 1996.

2. The following is a list of government personnel and contractors who have received pay from this contract:

Dr. Suzanne D. Smith, AL/CFBV, WPAFB OH
DynCorp, Inc. (Operation and Maintenance Contractor for Impact and Vibration Facilities), AL/CFBE, WPAFB OH